ABSTRACT
Recently Michelin has been developing a new airless, integrated tire and wheel combination called the Tweel® tire. The Tweel tire aims at performance levels beyond those possible with conventional pneumatic technology because of its shear band design, added suspension, and potentially decreased rolling resistance. In this paper, we will focus on the environmental impact of the Tweel tire during its lifecycle from manufacturing, through use and disposal. Since the Tweel tire is currently still in the research phase and is not manufactured and used on a large scale, there are uncertainties with respect to end-of-life scenarios and rolling resistance estimates that will affect the LCA. Nevertheless, some preliminary conclusions of the Tweel tire's environmental performance in comparison to a conventional radial tire can be drawn.

INTRODUCTION
The Tweel tire (the name is a contraction of “tire” and “wheel”) is an airless one-piece wheel-and-tire combination with a rubber tread bonded to a wheel hub with polyurethane spokes as shown in Figure 1. The Tweel tire aims at performance levels beyond those possible with conventional pneumatic technology because of its shear band design, added suspension, and decreased rolling resistance. It delivers pneumatic-like load-carrying capacity, ride comfort, and as it has no pressurized air cavity, it cannot fail by loss of air pressure. Eventually it may be able to outperform conventional tires since it can be designed to have high lateral stiffness for better handling without a loss in comfort.

However, it is unclear what environmental impact this radical new design will have. Currently there are environmental issues all throughout a tire's lifespan from rubber manufacturing emissions to tire disposal, and the rapidly growing method to evaluate all of these points is Life Cycle Analysis (LCA). LCA is the essential tool required by businesses in order to understand the total environmental impact of their products - cradle-to-grave. By considering the entire life cycle of a Tweel tire assembly from manufacturing, through use and disposal, and comparing it to knowledge of current tires, an assessment of its environmental impact will be made in this paper.

---

1. “Tweel” is a registered trademark of Michelin North America, Inc.
LIFE-CYCLE ANALYSIS

According to the life cycle analysis (LCA) standard ISO 14040, LCA is defined as “a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle.”[2] LCA is a technique for assessing all of the environmental aspects associated with a product from “cradle-to-grave”, or from a product's manufacturing stage through its life, and into its disposal route. This environmental assessment tool is critical to the foundation of this report and will be used extensively to compare the Tweel tire to a standard pneumatic, or air-filled, tire by adhering to the standards ISO 14040, 14041, 14042, 14043, 14404, and more recent ISO14046. These standards outline a basic four step process to complete a life cycle analysis consisting of a goal and scope, inventory analysis, impact assessment, and interpretation. There is a logical progression through these steps, but changes to any step throughout the analysis will have effects through other stages, so this becomes somewhat of an iterative process until a valid scope is defined that leads to an impact assessment that can be verified with confidence. The analysis in this report will be performed using this rough outline with a consistent goal to compare Michelin's Tweel tire to a current pneumatic radial tire.

To facilitate the study, we used the SimaPro version 7.1 LCA software developed by PRé Consultants. SimaPro features a user interface that allows the environmental inventory of any product or process to be modeled by specifying inputs (resources, fuels, electricity) and outputs (emissions to air, water, and soil, etc.). Each component of every phase of a product's life can be modeled separately and then combined to form a complete model of the entire life cycle. These components, such as raw materials production or disposal routes, can either be developed as new data sets by the user or existing pre-packaged databases that contain detailed environmental inventory data for thousands of products and processes across the world can be used. These databases (BUWAL, IDEMAT, Franklin USA, etc.) are developed by environmental professionals and are peer reviewed to assure confident data sets describing any potential environmental impact of a process, but each data set is usually geographically specific and may differ if the process is being modeled in a different country.

ASSUMPTIONS

GEOGRAPHIC BOUNDARY

Vehicle use differs across the world, but for the purposes of this report only U.S. data and emissions will be used when appropriate. In the case of some of the raw materials needed to produce a tire, the inventory data of required inputs and outputs will come from the country where the material is produced, and then the environmental costs of transporting that material to the U.S. will be added on. For example, natural rubber is almost entirely produced in Southeast Asia, so it would be inaccurate to assume it is produced in the U.S. to ignore the transportation emissions. For the majority of the analysis however, American standards and values will be used. The life cycle model will consider a tire made in the U.S., driven by an average American, and disposed of by ratios corresponding to American recycling plants.

Two very important differences arise between an American tire and a European tire. The average driving distance and tire use varies drastically between countries, but more importantly, the energy mix supplied by power plants in the U.S. is very different from that of a European country. The U.S. gets a larger percentage of its electricity from coal plants instead of wind and water power like some European countries, which directly affects the environmental impact of tire production that takes a large amount of electricity.[3]

The U.S. DoE's Energy Information Administration (EIA) updates the United States' energy mix numbers every year [4], so the American energy data used throughout this report will be representative of the EIA's numbers shown in Table 1.

| Table 1. DoE EIA energy mix, 2008 [4] |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                 | Coal            | Natural Gas     | Crude Oil       | Nuclear         | Hydro           |
| Total Production| 23,855,616      | 21,150,164      | 10,519,487      | 8,455,236       | 2,452,073       |
| Billion TWh     | (6,991)         | (6,199)         | (3,083)         | (2,478)         | (719)           |
| Percentage of Total | 36%        | 32%             | 15%             | 13%             | 3%              |

So, for these reasons it is important to distinguish that this is a U.S. analysis. Thus, all estimates will only be valid for American tires, so conclusions about the environmental effects of European tires should be made with caution.

LCA IMPACT CATEGORIES: EI99 AND EDIP

The ISO 14040 and 14046 documents provide a solid framework to assess the impact of the life cycle inventory, but their generalizations provide room for a variety of different impact assessment techniques. A number of different impact assessment methodologies are available to the LCA practitioner, and several of them are implemented in software commercially available on the market. For the purposes of this report, the EcoIndicator99 method will be the primary impact assessment tool used, but the EDIP2003 method will be used for validation to ensure that the results are not skewed simply because of the wrong choice of impact assessment methods. A fundamental difference between these two methods is that the Environmental Design of Industrial Products (EDIP) method has a problem-oriented approach to impact assessment as opposed to the EcoIndicator method,
which has a damage-oriented approach. This means that whereas the EDIP method models the impacts between emissions and damages, EcoIndicator aims its assessment directly at the damages caused by the emissions. This difference in approach will give two very different views on the collected life cycle inventory, which will greatly contribute to the validity of the results if the two assessments agree on the relative environmental impacts of the non-pneumatic compared to a conventional tire.

MATERIAL COMPOSITION

The production of a new tire is a fairly complicated process that involves many steps at a manufacturing plant, but before they can be considered, it must be understood how the necessary raw materials made it to the plant in the first place. Tables 2 and 3 describe the material composition of both functional units (P205/45R17 and an equivalent Tweel tire) that will be analyzed throughout their life cycles. The details of the production processes of each of these raw materials are described in this section and all the Life Cycle Inventory (LCI) data quantifying the material inputs and emissions are provided in [6].

### Table 2. P205/45R17 tire material composition [7]

<table>
<thead>
<tr>
<th>Raw material</th>
<th>Tread wt %</th>
<th>Tread wt %</th>
<th>Total tire wt %</th>
<th>Hub wt %</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synthetic rubber</td>
<td>15.78</td>
<td>41.72</td>
<td>24.17</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Natural rubber</td>
<td>24.66</td>
<td>3.53</td>
<td>18.21</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Carbon Black</td>
<td>23.40</td>
<td>9.54</td>
<td>19.00</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Silica</td>
<td>0.80</td>
<td>28.07</td>
<td>9.65</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Sulfur</td>
<td>1.80</td>
<td>0.80</td>
<td>1.28</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>ZnO</td>
<td>1.83</td>
<td>0.91</td>
<td>1.58</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Oil</td>
<td>4.02</td>
<td>10.64</td>
<td>6.12</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Stearic Acid</td>
<td>0.87</td>
<td>1.47</td>
<td>0.96</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Recycled rubber</td>
<td>0.60</td>
<td>0</td>
<td>0.50</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Coated wires</td>
<td>17.2</td>
<td>0</td>
<td>11.4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Textile</td>
<td>7.0</td>
<td>0</td>
<td>4.7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Steel</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Totals %</td>
<td>100.0</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>7.29</td>
<td>2.75</td>
<td>10.0</td>
<td>4.0</td>
<td>15.75</td>
</tr>
</tbody>
</table>

### Table 3. Michelin Tweel tire material composition [7]

<table>
<thead>
<tr>
<th>Raw material</th>
<th>Tread wt %</th>
<th>Spokes wt %</th>
<th>Hub wt %</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synthetic rubber</td>
<td>0</td>
<td>41</td>
<td>0</td>
<td>0.15</td>
</tr>
<tr>
<td>Natural rubber</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>0.10</td>
</tr>
<tr>
<td>Carbon Black</td>
<td>0</td>
<td>10</td>
<td>0</td>
<td>0.26</td>
</tr>
<tr>
<td>Silica</td>
<td>0</td>
<td>26</td>
<td>0</td>
<td>0.77</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0.02</td>
</tr>
<tr>
<td>ZnO</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0.03</td>
</tr>
<tr>
<td>Oil</td>
<td>0</td>
<td>11</td>
<td>0</td>
<td>0.29</td>
</tr>
<tr>
<td>Stearic Acid</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0.04</td>
</tr>
<tr>
<td>Recycled rubber</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Coated wires</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0.62</td>
</tr>
<tr>
<td>Textile</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>90</td>
<td>0</td>
<td>100</td>
<td>8.44</td>
</tr>
<tr>
<td>Steel</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Totals %</td>
<td>100.0</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>6.35</td>
<td>2.75</td>
<td>2.65</td>
<td>4.0</td>
</tr>
</tbody>
</table>

MANUFACTURING OF P205/45R17 TIRE

The tire production process is a complicated one that involves several complex parts that are mated together. The general process of constructing a tire involves assembling the numerous components shown in Figure 2 and then vulcanizing these parts together to achieve the desired properties. The details of the production process of each tire manufacturer are difficult to find because of the confidentiality of their specific process, so for the purposes of this thesis, an average tire production process will be modeled. Combining this generic process with the specific material breakdown of a P205/45R17 tire described in section 4.1 will represent an average tire built anywhere across the country with the given specifications of a section width of 205 mm, aspect ratio of 45%, and a wheel rim diameter of 17 in. This generic and somewhat simplified tire production process is outlined in Figure 3. Each of these production stages has its own environmental inventory. They are described in [6], but omitted here for brevity.

The process begins with the mixing of basic rubbers with process oils, carbon black, accelerators and other additives. The environmental inventory of these basic ingredients has been described above, so simply considering the correct proportions described in Table 2 is all that is necessary to analyze the environmental impact of the raw materials entering the mixing process in the manufacturing plant. It is out of the scope of this paper to consider the transport of most of the raw materials to the tire manufacturing facility due to the difficulty of modeling the distribution of raw materials from multiple production sites to multiple tire production sites across the country. As a result, it will be assumed that the raw materials are produced near the manufacturing plant so this transportation can be ignored. Most LCAs of raw material productions already include a standard transportation distance and in general the transportation of domestically
produced bulk materials over a few hundred miles to a manufacturing plant has insignificant life-cycle effects. We can see this also in the results section where the distribution/transport of tires has negligible effects on the overall life-cycle impacts. Thus, the only thing to consider in this mixing stage is the intense heat and pressure required in this process, the water required to cool the mixing so that vulcanization does not occur prematurely, and any emissions that result from these extreme conditions. Details for the required heat and pressure are not well-documented, so the only source available for the environmental inventory of this mixing process is the EcoInvent database. PRé Consultants documented the entire tire production process in their life-cycle analysis of an average European tire, but due to some possible differences between European and American tire production, these values are only used as a comparison.\[10\]

This mixed rubber then takes all the different forms shown in Figure 2 - sidewalls, tread, liner, etc. Most of these sub-components are made by calendering or extruding the uncured rubber into the desired dimensions. Rough assumptions about the energy requirements and necessary lubricants in these two rubber processing techniques are taken from J.L. White's book titled Rubber Processing.\[11\] Transporting these rubber components around the factory takes place on rollers, so minimal energy or ancillary materials are required; as a result this transportation can be ignored. So, modeling the assembly process of all the components can be simplified to the rubber mixing process combined with the necessary lubricants and adhesives that secure the coated wires and textiles in place.

Once all the components are assembled, the “green” tire is cured or vulcanized to glue everything together and to achieve the final dimensions and rubber properties. This curing process takes place under conditions of roughly 350 degrees Fahrenheit with pressures around 350 psi for around 15 minutes.\[11\] Details for the energy requirements of this curing process are modeled in Han's report titled Dynamic Simulation of the Tire Curing Process.\[12\] After the curing process is complete, the finished tires are inspected (which requires no extra environmental resources), and are sent out for distribution. Again, details of these intermediate steps are not listed here in order to simplify the inventory, but the inventory data from these small processes are combined and presented in \[6\].

MANUFACTURING OF TWEEL TIRE

Two problems limit the ability to present a complete environmental inventory of the Tweel tire. One of them is the confidential nature of Michelin's invention and the second is the immaturity of the Tweel production process. The Tweel tire is not being mass produced yet, so there is only a hypothetical knowledge of the process requirements and capabilities available. The manufacturing inventory will be as thorough as possible, though.

Tweel tires are produced in three steps: tread, hub, and polyurethane. In the first step, the tread is constructed by a similar method as the tire tread manufacturing process. The tread on a Tweel tire is exactly the same as a pneumatic tire and is extruded in the same way, and it is mated to layers of belts in the same manner as conventional tires. The process of rolling plies onto a drum to achieve the correct diameter currently is performed manually, but the same basic process that is performed on tires will be mimicked when the Tweel production is fully automated. In this fairly simple process, rectangular sheets of rubber and steel cord are rolled onto a steel drum, and the excess material from each sheet is removed. Once the desired base thickness is achieved in this manner, the extruded tread is rolled onto the top, and the entire assembly is vulcanized. The second step is a very simple 4 kg steel hub casting that is well documented in several databases including BUWAL250.

In the third step, the hub and the tread are secured concentrically and polyurethane is poured into a spoke and shear band mold while the entire assembly spins so that the polyurethane will sufficiently fill the mold in the radial direction. The energy needed to spin the Tweel assembly and polyurethane mold for just 5 minutes while the polyurethane is poured is considered irrelevant compared to the large amount of energy required to heat and pressurize the ovens needed to cure the shear band and then cure the entire assembly after the polyurethane is poured, so it can be ignored in this inventory. Before the pouring process occurs though, all the surfaces that contact the polyurethane are cleaned and covered with either an adhesive or a mold release for the shear band and spoke mold, respectively. The quantities of these additives were supplied by Michelin, and are listed in Table 4.
The polyurethane pre-polymers and curative are stored separately until they are heated and combined at this point in the manufacturing process, but this chemical process is considered part of the raw materials production in order to analyze which material is causing the most amount of environmental harm. The combination of the heated pre-polymers and curative could be considered in this Tweel manufacturing section, but in order to organize the impacts of the raw materials it is treated as part of the raw material production of polyurethane. After the polyurethane is poured and the assembly is allowed to stop spinning, the entire Tweel tire (shear band, spokes, and hub) is placed into another oven. This final curing occurs at 100°C degrees for 4 hours so that the desired polyurethane properties are obtained and to assure all the components are securely bonded together. To save some energy this curing process could take place at room temperature, but it would take much longer to complete and during this time it would be susceptible to being bumped and permanently damaged, so this possible environmental benefit to save the energy required to heat the oven is not a plausible option for Michelin. So, this energy must be considered along with all the other process inputs mentioned, and all of these are organized with the rest of the life cycle inventory.

HEATING AND PRESSURIZING ENERGY
In both of these manufacturing processes, the most important factor that affects the environmental impact of these processes is the energy required to heat and pressurize the ovens and molds used to cure rubber and polyurethane.

The energy inputs for rubber curing presses have been recorded and analyzed by tire manufacturers, and the average tire curing process requires about 1.1 kWh of energy for a tire weighing 10 kg, which means roughly 0.11 kWh of energy is needed to vulcanize 1 kg of rubber. At the early stages of Tweel manufacturing, Michelin is using the same type of press that is used to cure radial tires, so it is assumed in this analysis that the same energy will be required to cure 1 kg of rubber in a Tweel tire as 1 kg of pneumatic tire rubber. The thickness of rubber in these two products varies slightly, but the curing temperature and time is close enough to assume the same energy requirements per kg of rubber. So, the required energy to cure the shear band in the Tweel is roughly (6.35 kg)*(0.11 kWh/kg), which equals 0.7 kWh.

The energy required to heat, mix, and cure the polyurethane is allocated to the raw material production of polyurethane, so this 0.7 kWh is all the energy that is needed in the Tweel manufacturing inventory.

THE STEEL HUB
Typically the hub is left out of tire life cycle analysis due to its relative longevity compared to the life of the rubber, but it will be included in the analysis for both products in this thesis because of the way it is molded to the spokes of a Tweel tire. Separating a Tweel tire from its hub is not as simple as the process for a tire because the polyurethane spokes of a Tweel tire are molded directly to the steel hub with a bond that is not easily broken, so for consistency the hub will be included in both life cycle analyses. Both products use a steel hub weighing roughly 4 kg, but the entire environmental impact of this large amount of steel should not be considered as part of one conventional or Tweel tire life cycle because each hub lasts much longer than the rubber or polyurethane components of a tire or Tweel tire and can be used through roughly 4 tire life cycles. For this reason, only 1/4 of the environmental impact of the 4 kg hub from each product will be considered in this analysis, i.e., 1 kg steel. The entire life cycle of the steel hub will be considered from raw material production to casting to recycling, but it will be assumed that only 1 kg of steel is relevant to one life cycle due to the much longer use life compared to the rest of a conventional or Tweel tire.

USE PHASE FUEL CONSUMPTION
The most important aspect of the use phase of a tire, or the lifetime the tire is used on a car, is the amount of fuel it consumes. The amount of fuel consumed by a vehicle over a distance is affected by the overall efficiency of the vehicle in converting the chemical energy in motor fuel into mechanical energy and transmitting it to the axles to drive the wheels. However, not all of the fuel used by a car is used to drive the wheels, so only a certain percentage of the fuel used by a car should be allocated to the wheels and used in this analysis. Sources estimate that the rolling resistance of tires accounts for about 5 to 10% of the fuel used in a passenger vehicle, so only this percentage of fuel used over the entire life of the wheel should be included in this inventory. Rolling resistance is defined as the amount of force needed to roll a vertically loaded tire at a constant speed, and is represented in terms of a rolling resistance coefficient (RRC) in units of kg/ton (required thrust force/vertical load), which is constant for a given wheel under any vertical load. Wind resistance is not a factor here, simply the energy loss due to cyclic deformation of viscoelastic rubber.

Tables 5 and 6 include data supplied by Michelin that describe the effects of rolling resistance on fuel economy. Table 5 lists top nine passenger vehicles on the road today and their average city and highway fuel economy. So,
In that same report, it is stated that 55% of driving occurs on urban roads while 45% is done on highways, so by taking 55% of 10.7 L/100km and combining that with 45% of 7.4 L/100km gives the 9.22 L/100km value shown in Table 6 under the RRC of 10.[8] Note that all of the vehicles listed in Table 5 run on gasoline, so this inventory assumes no diesel fuel use and 100% gasoline use.

### Table 5. Average fuel economy of passenger car fleets

<table>
<thead>
<tr>
<th>MODEL</th>
<th>Total</th>
<th>Curb Weight (lbs)</th>
<th>City Economy (mpg)</th>
<th>HWF Economy (mpg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAMRY</td>
<td>4380631</td>
<td>3260</td>
<td>21</td>
<td>31</td>
</tr>
<tr>
<td>ACCORD</td>
<td>4327067</td>
<td>3400</td>
<td>21</td>
<td>31</td>
</tr>
<tr>
<td>CIVIC</td>
<td>3546835</td>
<td>2770</td>
<td>25</td>
<td>36</td>
</tr>
<tr>
<td>COROLLA</td>
<td>2995572</td>
<td>2820</td>
<td>26</td>
<td>35</td>
</tr>
<tr>
<td>TAURUS</td>
<td>2818465</td>
<td>3640</td>
<td>18</td>
<td>28</td>
</tr>
<tr>
<td>IMPALA</td>
<td>2338172</td>
<td>3680</td>
<td>18</td>
<td>29</td>
</tr>
<tr>
<td>ALTIMA</td>
<td>2280732</td>
<td>3130</td>
<td>23</td>
<td>31</td>
</tr>
<tr>
<td>MALIBU</td>
<td>2167215</td>
<td>3300</td>
<td>22</td>
<td>30</td>
</tr>
<tr>
<td>FOCUS</td>
<td>2070687</td>
<td>2588</td>
<td>24</td>
<td>33</td>
</tr>
<tr>
<td>Total</td>
<td>26925376</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Weighted Averages**

<table>
<thead>
<tr>
<th>US (lbs, mpg)</th>
<th>SI (kg, l/100km)</th>
<th>3186</th>
<th>22.0</th>
<th>31.7</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1445</td>
<td>10.7</td>
<td>7.4</td>
<td></td>
</tr>
</tbody>
</table>

### Table 6. Fuel economy (L/100km) changes with increasing Rolling Resistance Coefficient (RRC)

<table>
<thead>
<tr>
<th>Drive Cycle</th>
<th>RRC (kg/ton)</th>
<th>3</th>
<th>4</th>
<th>5.5</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>11.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>FTP 75</td>
<td>9.98</td>
<td>10.08</td>
<td>10.24</td>
<td>10.29</td>
<td>10.49</td>
<td>10.70</td>
<td>10.85</td>
<td></td>
</tr>
<tr>
<td>HWFET</td>
<td>6.61</td>
<td>6.72</td>
<td>6.89</td>
<td>6.95</td>
<td>7.17</td>
<td>7.40</td>
<td>7.56</td>
<td></td>
</tr>
<tr>
<td>Combined</td>
<td>8.46</td>
<td>8.57</td>
<td>8.73</td>
<td>8.79</td>
<td>9.00</td>
<td>9.22</td>
<td>9.37</td>
<td></td>
</tr>
<tr>
<td>NEDC</td>
<td>10.47</td>
<td>10.58</td>
<td>10.73</td>
<td>10.79</td>
<td>11.00</td>
<td>11.21</td>
<td>11.36</td>
<td></td>
</tr>
</tbody>
</table>

The rest of Table 6 was populated by Michelin using their own rolling resistance calculating methods with respect to this baseline average tire, and although the fuel economies with a RRC below 6 are purely theoretical, they are still relatively reliable. No standard deviation or uncertainty was supplied with this table, so it will be assumed that these calculations are accurate, although it is important to note that these values were derived from a theoretical formula and currently there are no tires with a low enough rolling resistance to check the very small RRC fuel economy values.

One of Michelin's design goals is to achieve roughly 10% lower rolling resistance than a fuel efficient tire through the use of conventional tire materials and commercially available polyurethanes. In this analysis a hypothetical Tweel tire meeting that target will be compared against a tire with the best rolling resistance characteristics on the market today. According to the Transportation Research Board's report this low end of the spectrum occurs at a rolling resistance of about 6 kg/ton.[8] Bridgestone's B381 tire has a rolling resistance of 6.2 kg/ton while Michelin's Symmetry tire is measured around 6.5 kg/ton.[18] Thus by the values supplied in Table 6, the combined fuel economy for the P205/45R17 tire analyzed in this report is 8.79 L/100km (26.8 mpg).

Table 6 can now be used to evaluate the amount of fuel used by the wheels by comparing the relative fuel savings from differing levels of rolling resistance. The key fact in the fuel economy table is that everything on the vehicle is held constant except the rolling resistance, so all fuel savings with a decreased RRC is a result of only the wheel. Comparing this knowledge between the average fuel consumption of a 6 kg/ton tire and 5.5 kg/ton Tweel tire having fuel economies of 8.79 and 8.73 L/100km respectively, shows that a 5.5 kg/ton Tweel tire could result in a fuel savings of 0.06 L/100km.

The average life of a tire is determined by finding the ratio of the number of vehicles in the United States to the national replacement tire sales. This ratio (175 million/200 million = 0.88) suggest that a motorist can expect to purchase a replacement tire an average of every 0.88 years, or a complete set of four tires about every 3.5 years. (4 × 0.88 = 3.52).[8] Multiplying this by the average annual vehicle mileage of 12,000 miles, the total life of a tire is found to be roughly 42,000 miles (3.5 years × 12,000 miles/year).[19, 20] Multiplying the fuel consumption rate of a wheel by this lifetime mileage give the total fuel used by all four tires, so this final number must be divided by 4 to find the total fuel consumption by one tire over its life. In this analysis it is assumed that the Tweel tires have the same lifespan of 42,000 miles, but there is some evidence to suggest that a lower rolling resistance and different construction altogether may increase the service life of a Tweel tire. Data are limited on this topic and entirely theoretical, so that possible difference will be ignored in this thesis, but it may deserve some extra research in the future. A sample calculation for the total fuel consumed by the reference 6 kg/ton tire is shown in Equation 1 and the consumptions are summarized in Table 7.

![Equation 1](image)
Table 7. Total fuel use over lifetime of one tire

<table>
<thead>
<tr>
<th>Tire</th>
<th>Rolling Resistance Coefficient (kg/ton)</th>
<th>Vehicle Fuel Economy (L/km)</th>
<th>Tire Fuel Consumption (L/km)</th>
<th>Total Fuel Use (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P205/45R17 Tire</td>
<td>6</td>
<td>0.0879</td>
<td>0.006</td>
<td>101</td>
</tr>
<tr>
<td>Tweel Tire</td>
<td>5.5</td>
<td>0.0873</td>
<td>0.0054</td>
<td>91</td>
</tr>
</tbody>
</table>

END OF LIFE

Since the polyurethane can be separated from the rubber tread in a Tweel tire at the end of its life, this analysis assumed both materials will be disposed of separately, which simplifies the environmental assessment to a combination of rubber (whole tire and Tweel tread) and polyurethane treated separately. The national average disposal route (i.e., landfill, tire derived fuel, civil engineering purposes, tire recycling) percentages for both materials were analyzed individually and then combined in the appropriate weight percentages for both a conventional and a Tweel tire. Considering the rubber first, the tread separated from a Tweel (done through a specified heating method) is assumed to have the same material properties and composition as rubber from a tire in order to group both rubber sources together for simplification. The tread from a Tweel tire has no wires and thus will produce no scrap metal upon grinding, but all other properties are assumed to be equal.

RESULTS

By combining all of the stages from “cradle to grave,” a picture of the overall environmental effects of the entire life cycle can be assembled. This life cycle analysis predicts the environmental impact of one tire or Tweel tire beyond simply the energy required to manufacture either, for example. Figure 4 and Figure 6 describe the relative environmental effects of each stage of a P205/45R17 tire’s life cycle, while Figure 5 and Figure 7 illustrate the life cycle analysis for one Tweel tire.

The production phase combines the production of raw materials with the manufacturing of a tire or Tweel tire, and similarly the end of life phase combines all the disposal routes. The use phase on the other hand is separated into the effects of tread wear and gasoline usage so that the most important aspect of each product’s life cycle, the fuel use, can be accurately compared to both of the other main phases, production and disposal. The distribution phase assumes most of the raw materials are produced near the tire or Tweel manufacturing plants, but it illustrates the effect of transporting one product from the manufacturer to the retailer at the start of its life combined with the transportation from the retailer to the disposal site and the end of its life. As can be seen, distribution impacts exist, but are negligible.

Figure 4. P205/45R17 Tire Life Cycle Analysis (10 kg tire w/1 kg steel hub) (Method: EcoIndicator99(E) V2.05 / EuropeE199E/E / single score)

Figure 5. Tweel Life Cycle Analysis (12 kg Tweel with 1 kg steel hub) (Method: EcoIndicator99(E) V2.05 / EuropeE199E/E / single score)
Table 9. Data for Figure 5 [Pt]

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Production</th>
<th>Distribution</th>
<th>Tread Debris</th>
<th>Fuel Use</th>
<th>End of Life</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carcinogens</td>
<td>0.016</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.001</td>
<td>0.024</td>
</tr>
<tr>
<td>Respiratory organics</td>
<td>0.004</td>
<td>0.000</td>
<td>0.000</td>
<td>0.010</td>
<td>-0.001</td>
<td>0.013</td>
</tr>
<tr>
<td>Respiratory inorganics</td>
<td>1.193</td>
<td>0.001</td>
<td>1.974</td>
<td>6.373</td>
<td>-0.215</td>
<td>9.326</td>
</tr>
<tr>
<td>Climate change</td>
<td>0.235</td>
<td>0.000</td>
<td>0.000</td>
<td>2.132</td>
<td>-0.018</td>
<td>2.349</td>
</tr>
<tr>
<td>Radiation</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Ozone layer</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Ecotoxicity</td>
<td>0.038</td>
<td>0.000</td>
<td>2.436</td>
<td>0.000</td>
<td>0.343</td>
<td>2.817</td>
</tr>
<tr>
<td>Acidification/Eutrophication</td>
<td>0.213</td>
<td>0.000</td>
<td>0.000</td>
<td>1.912</td>
<td>-0.029</td>
<td>2.967</td>
</tr>
<tr>
<td>Land use</td>
<td>0.075</td>
<td>0.000</td>
<td>0.000</td>
<td>0.062</td>
<td>-0.001</td>
<td>0.136</td>
</tr>
<tr>
<td>Minerals</td>
<td>0.004</td>
<td>0.000</td>
<td>0.000</td>
<td>0.001</td>
<td>0.000</td>
<td>0.004</td>
</tr>
<tr>
<td>Fossil fuels</td>
<td>3.116</td>
<td>0.001</td>
<td>0.000</td>
<td>17.462</td>
<td>-0.639</td>
<td>19.939</td>
</tr>
<tr>
<td>Total</td>
<td>4.864</td>
<td>0.002</td>
<td>4.418</td>
<td>27.952</td>
<td>-0.559</td>
<td>38.707</td>
</tr>
</tbody>
</table>

Figure 6. Tire Life Cycle Analysis (Method: EDIP 2003 V1.00 / Default / single score)

Table 10. Data for Figure 6 [EDIP mPt]

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Production</th>
<th>Distribution</th>
<th>Tread Debris</th>
<th>Fuel Use</th>
<th>End of Life</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global warming 100a</td>
<td>8.51</td>
<td>0.00</td>
<td>0.00</td>
<td>87.15</td>
<td>-3.10</td>
<td>92.56</td>
</tr>
<tr>
<td>Ozone depletion</td>
<td>4.65</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.03</td>
<td>4.68</td>
</tr>
<tr>
<td>Ozone formation (Vegetation)</td>
<td>3.36</td>
<td>0.01</td>
<td>0.01</td>
<td>64.87</td>
<td>-1.72</td>
<td>66.63</td>
</tr>
<tr>
<td>Ozone formation (Human)</td>
<td>3.34</td>
<td>0.01</td>
<td>0.01</td>
<td>61.91</td>
<td>-1.72</td>
<td>63.54</td>
</tr>
<tr>
<td>Acidification</td>
<td>0.93</td>
<td>0.00</td>
<td>0.00</td>
<td>21.81</td>
<td>-0.21</td>
<td>22.22</td>
</tr>
<tr>
<td>Terrestrial eutrophication</td>
<td>2.17</td>
<td>0.01</td>
<td>0.00</td>
<td>54.51</td>
<td>-1.03</td>
<td>55.55</td>
</tr>
<tr>
<td>Aquatic eutrophication EP(N)</td>
<td>1.55</td>
<td>0.00</td>
<td>0.00</td>
<td>36.05</td>
<td>-0.64</td>
<td>36.69</td>
</tr>
<tr>
<td>Aquatic eutrophication EP(P)</td>
<td>0.49</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-0.03</td>
<td>0.46</td>
</tr>
<tr>
<td>Human toxicity air</td>
<td>3.75</td>
<td>0.01</td>
<td>0.07</td>
<td>11.72</td>
<td>0.38</td>
<td>15.93</td>
</tr>
<tr>
<td>Human toxicity water</td>
<td>23.83</td>
<td>0.00</td>
<td>0.15</td>
<td>0.02</td>
<td>-23.99</td>
<td>0.01</td>
</tr>
<tr>
<td>Human toxicity soil</td>
<td>26.64</td>
<td>0.13</td>
<td>1.04</td>
<td>18.04</td>
<td>-0.95</td>
<td>44.90</td>
</tr>
<tr>
<td>Ecotoxicity water chronic</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Ecotoxicity water acute</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Ecotoxicity soil chronic</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Hazardous waste</td>
<td>0.08</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.08</td>
</tr>
<tr>
<td>Slugs/ashes</td>
<td>0.10</td>
<td>0.00</td>
<td>0.00</td>
<td>0.02</td>
<td>-0.01</td>
<td>0.11</td>
</tr>
<tr>
<td>Bulk waste</td>
<td>0.92</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.94</td>
</tr>
<tr>
<td>Radiotoxic waste</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Resources (all)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>80.31</td>
<td>0.18</td>
<td>1.28</td>
<td>355.93</td>
<td>-32.95</td>
<td>404.71</td>
</tr>
</tbody>
</table>

Table 11. Data for Figure 7 [EDIP mPt]

Figure 7. Tweel Life Cycle Analysis (Method: EDIP 2003 V1.00 / Default / single score)

As both the EcoIndicator and EDIP assessment methods are presented on different vertical scales representing their unique method of weighing each impact category, direct comparisons between the two methods is impossible (33 Pt EcoIndicator fuel use phase is not 100 times more environmentally harmful than the 350 mPt EDIP fuel use phase). The relative impacts between each life cycle phase though are important. The first comparison that summarizes most of the details of the life cycle of both products is that the
fuel consumed by rolling resistance is by far the most environmentally harmful portion of a wheel's life cycle. The overall effects of producing the necessary amount of gasoline and then burning it to overcome rolling resistance for 42,000 miles is 5 or 6 times that of the next most harmful phase, the production phase, according to both impact assessment methods. The EcoIndicator values the tire use phase over the next most important phase, the tire production, 30.88 Pt to 4.95 Pt, while the Tweel impacts in these two phases differs 570% between 27.95 Pt to 4.89 Pt. The EDIP method shows similar dominance by the use phase over any other phase quantifying the environmental impact of a tire as 450% more important than any other phase (356 mPt to 80 mPt) while the gap remains similar with a Tweel at a 380% difference between the 322 mPt use phase and the 84 mPt production phase. The two methods disagree on the relative environmental impact of the rubber debris, but the rest of the life cycle phases show remarkable similarity. The production of each product contributes less than 20% of the environmental impact of the use phase while the environmental benefits of the end of life impact either negate or slightly overcome the negative impact from emissions and energy use, and the effects of distributing one wheel compared to these other stages is negligible.

Note that end of life phases are negative in Figures 4, 5, 6, 7, meaning that they reduce environmental impacts. Due in part to the slight variation in landfill impacts between polyurethane and rubber and in part to the small percentage of polyurethane recycling in the United States today, the Tweel end of life scenario is shown to be slightly less environmentally beneficial compared to a conventional tire. Also, extra energy is required to heat a Tweel tire enough to separate the Polyurethane from the rubber tread even before any of the processing is performed, which will offset some of the benefits due to the recycling of both components. The EDIP method estimates that disposing of one Tweel (considering the national averages of both polyurethane and rubber disposal methods) is only about 45% as beneficial to the environment as a tire.

The benefit of portraying the effects of each stage of the life cycle on one uniform scale is that the slightly more harmful Tweel production and disposal phases can now be compared directly to its environmental savings as a result of the decreased fuel use due to its lower rolling resistance. The Tweel production process is slightly more environmentally harmful due to the effects of polyurethane and the additives like mold release needed to manufacture it along with the overall increased mass, and the disposal phase (although most of this analysis is hypothetical) will most likely be less beneficial because of the current state of polyurethane recycling. However, the two impact assessment methods allow these cons to be weighed against the pros of fuel savings in a manner that simply quantifying the CO₂ emissions cannot. It also allows the life cycle phases to be added together to provide an overall environmental score for every aspect of a Tweel tire so that one statement can be made that assesses whether it is better or worse overall than a conventional fuel efficient tire. The assumption that producing a Tweel tire saves CO₂ tailpipe emissions while requiring more SO₂ emissions in the production phase as described in Table 12 is useful, but without the EcoIndicator and EDIP impact assessment methods it is very difficult to quantify this tradeoff as beneficial.

**EMISSIONS COMPARISON**

The life-cycle airborne emissions were also compared to provide insight into of the life cycle impact of these products. As described in Table 12, the fuel use is responsible for most of the major airborne emissions, which is a large contributing factor to the dominance of that phase in the overall life cycle impact. The CO₂ emissions in the use phase of a state of the art, fuel efficient pneumatic tire and a hypothetical, fuel efficient Tweel tire total 522 kg and 472 kg, respectively, as compared to the production phase which only produces 26.9 kg and 53.2 kg of CO₂ respectively (1900% and 9% differences). These wide gaps are diluted by all the other small inputs and outputs in the production phase that cannot be organized into a simple table like Table 12, returning the overall importance of the fuel use phase over the production phase to 450% for a tire and 380% for a Tweel.

**Table 12. Selected emissions to air per life cycle phase**

<table>
<thead>
<tr>
<th>Emission</th>
<th>Production</th>
<th>Distribution</th>
<th>Tread Debris</th>
<th>Fuel Use</th>
<th>End of Life</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ - Tire (kg)</td>
<td>26.9</td>
<td>0.029</td>
<td>0</td>
<td>522</td>
<td>-15.8</td>
<td>533.1</td>
</tr>
<tr>
<td>CO₂ - Tweel (kg)</td>
<td>53.2</td>
<td>0.035</td>
<td>0</td>
<td>472</td>
<td>-4.9</td>
<td>520.4</td>
</tr>
<tr>
<td>CO - Tire (g)</td>
<td>4.95</td>
<td>0.008</td>
<td>0</td>
<td>519</td>
<td>-1.1</td>
<td>522.9</td>
</tr>
<tr>
<td>CO - Tweel (g)</td>
<td>5.12</td>
<td>0.009</td>
<td>0</td>
<td>470</td>
<td>-0.4</td>
<td>474.7</td>
</tr>
<tr>
<td>N₂O - Tire (g)</td>
<td>2.15</td>
<td>0.0009</td>
<td>0</td>
<td>101</td>
<td>-0.3</td>
<td>102.9</td>
</tr>
<tr>
<td>N₂O - Tweel (g)</td>
<td>0.46</td>
<td>0.0011</td>
<td>0</td>
<td>91.8</td>
<td>-0.1</td>
<td>92.2</td>
</tr>
<tr>
<td>SO₂ - Tire (g)</td>
<td>6.32</td>
<td>0</td>
<td>0.26</td>
<td>237</td>
<td>14.4</td>
<td>258.0</td>
</tr>
<tr>
<td>SO₂ - Tweel (g)</td>
<td>51.7</td>
<td>0</td>
<td>0.26</td>
<td>215</td>
<td>-3.3</td>
<td>263.7</td>
</tr>
</tbody>
</table>

The raw emissions life cycle totals can be helpful though to begin determining which product is more environmentally friendly overall. Summing up each of the emissions in Table 12 shows that a Tweel tire achieving the design target would produce 13 kg less CO₂, 48 g less CO, 10 g less N₂O, but 6 g more SO₂. These totals establish the Tweel tire as generally less harmful in terms of these emissions, but as with comparing the use phase to the production phase, the entire collected inventory must be considered to determine which product has a smaller environmental load most accurately.
OVERALL IMPACT

Table 13 and 14 list the environmental impact scores from Figures 4, 5, 6, 7 interpreted by both the EcoIndicator and EDIP assessment methods.

<table>
<thead>
<tr>
<th>Table 13. Total environmental impact over entire life cycle - EcoIndicator (Pt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
</tr>
<tr>
<td>Tire</td>
</tr>
<tr>
<td>Tweel</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 14. Total environmental impact over entire life cycle - EDIP (mPt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
</tr>
<tr>
<td>Tire</td>
</tr>
<tr>
<td>Tweel</td>
</tr>
</tbody>
</table>

Again it can be seen that the use phase is the most environmentally harmful stage of the life cycle, but as all of the numbers in each table are on the same weighted scale, the impacts of all the stages can be summed up to give one single score representing the environmental impact of the entire life cycle of each product. According to the EcoIndicator method, a 5.5 kg/T Tweel tire would be 2.61 Pts less harmful to the environment than the most fuel efficient tire on the market today. So, even though its environmental load is slightly higher in the production phase, the 10% decrease in rolling resistance results in a 6% environmental savings overall. Similar results are found with the EDIP method even though it is presented on a different scale in which a 5.5 kg/T Tweel tire is assessed as 6.86 mPts better than the pneumatic tire, or an overall savings of roughly 2%. The EDIP method assesses the Tweel tire's production and end of life phases a little more harshly than the Ecolnicator method, but both agree that at 5.5 kg/T, the Tweel tire would be more environmentally friendly overall than the most fuel efficient conventional tire available when every phase of the life cycle is considered.

Although both of the chosen impact assessment methods have different weights and scales that result in overall impacts that slightly differ from each other, a simple comparison can be made between the importance of climate change or global warming since both methods contain this impact category. As shown in Table 15 below, the EDIP emphasizes its “global warming” category much higher than the EcoIndicator’s “climate change” category by a spread of about 23% to only 6%. The EcoIndicator method stresses the use of fossil fuels and emissions that cause respiratory damage while global warming and ozone damage are much more important to the EDIP method. Even though differences such as these exist, the life cycle analyses of both impact assessment methods agree remarkably well with each other, supporting the important point that life cycle impacts of both products do not depend greatly on the choice of the impact assessment method.

<table>
<thead>
<tr>
<th>Table 15. Climate change impact relative to overall LCA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
</tr>
<tr>
<td>Tire</td>
</tr>
<tr>
<td>Tweel</td>
</tr>
</tbody>
</table>

SUMMARY AND DISCUSSION

Figure 8 graphs the single score environmental impacts of both a state of the art, fuel efficient tire and a hypothetical Tweel tire achieving Michelin's design target in each life cycle phase using both the EcoIndicator and EDIP assessment methods. As each method weights its results on different scales, the figure plots each assessment method on a different scale and compares the two by setting the fuel use categories equal to each other. This does not mean that the EDIP rates the production phases of both products as more environmentally harmful though; this is an artifact due to the arbitrary scaling. If the different vertical scales were compared by equating the tire production phases, then the EDIP use phase would be presented as less environmentally harmful than that resulting from the EcoIndicator scale. So, instead of making direct comparisons between the scores between, say, the EcoIndicator and EDIP ratings of the tire production phase, Figure 8 illustrates the importance of the use phase and how the 10% benefit from the targeted Tweel tire fuel savings outweighs the small drawback of the increased environmental load of the production and end of life phases. Although they disagree on the impact of the rubber debris, both impact assessment methods agree on this result alluded to by the difference in select air emissions described in Table 12.

For simplification the positive and negative scores present simultaneously in the end of life phases have been added together to give one overall score. This removes some of the detail needed to describe the full end of life phase, but makes it more comparable to the other phases’ single scores.

A 10% lower Tweel tire rolling resistance would result in a 2 to 6% overall environmental improvement depending on the assessment method chosen, but these results are based on a few assumptions. Most importantly, Tweel tires are currently not in mass production and changes are still being made to the design, so the production process may change slightly. Only minor changes are expected though; none of which would have a noticeable impact on the life cycle analysis. However, these changes might have a small impact on the
expected 10% rolling resistance reduction that may impact the 42,000 mile lifespan. At this point the 5.5 kg/ton value is still only a design target, and this study serves mainly to confirm the environmental value of achieving that target.

![Graph showing LCA Comparisons of P205/45R17 tire and Tweel on similar scale](image)

Figure 8. LCA Comparisons of P205/45R17 tire and Tweel on similar scale

Also, the end of life phase of a Tweel tire provides only about half the environmental benefit experienced by that of a tire, but this may improve if Polyurethane landfilling gains as much publication as the dangers of whole tire landfilling. The Tweel tire end of life phase, although still beneficial to the environment when the avoided energy or polyurethane production is considered, has a large impact on decreasing the 10% fuel savings to only a 2 to 6% life cycle environmental savings. If the Tweel tire end of life stage was to have the same overall environmental effects as a tire's end of life, the overall environmental savings of a Tweel tire compared to a tire would rise to 7%. If millions of Tweel tires start piling up in landfills in the same way that tires have, a push to find better ways to incinerate and reuse polyurethane may develop, which could possibly reduce the 74% of polyurethane currently amassing in landfills. This may result in a more environmentally beneficial end of life phase.

**CONCLUSION**

In concluding the goal and scope of this analysis it was found that Michelin's design goal of a very low rolling resistance Tweel tire could result in at least equivalent if not more environmentally friendly performance than the most fuel efficient tire on the market today when the overall life cycles of both are considered due to its fuel savings. Both the EcolIndicat99 and EDIP assessment methods agree that producing and disposing of a non-pneumatic Tweel tire contributes a slightly higher environmental load than the baseline tire, but the hypothetical Tweel tire benefits from the 10% fuel savings when it is used on a vehicle. Due to the much higher contribution from the use phase (5 times higher impact score, 10 times more carbon dioxide emissions, and 100 times more carbon monoxide), this fuel saving would outweigh the environmental drawbacks of producing a large amount of polyurethane and the additives needed to mold it and adhere it to the hub and the rubber tread resulting in an overall environmental improvement if one replaces conventional tires with Tweel tires. With the current knowledge available, the best estimate for the life cycle comparison would be a 2 to 6% relative environmental savings with a 5.5 kg/T Tweel tire as compared to a conventional fuel efficient tire with a rolling resistance of 6 kg/ton.

**ACKNOWLEDGMENTS**

We would like to acknowledge Chris Madden and Dr. Tim Rhyne along with Jim Endicott of Michelin North America for providing funding, data and expert advice. We would also like to acknowledge Ralph Hulseman (formerly at Michelin) for initiating the project as part of NIST's Advanced Technology Program project “Michelin Energy Efficient Non-Pneumatic Tire and Wheel (Tweel Assembly)”. We gratefully acknowledge the George W. Woodruff School of Mechanical Engineering and the Manufacturing Research Center for their continued in kind support.

**REFERENCES**


Transportation Research Board of the National Academies; 2006, Washington, DC :: Transportation Research Board.


14. Grosch, K. Rubber Abrasion and Tire Wear. 2007: American Chemical Society, 1155 16 th St, NW, Washington, DC, 20036, USA.


