Winning Solar Races With Interface Design

BY ANTONY HILLIARD & GREG A. JAMIESON

Applying representation aiding to solar car racing can boost performance and potentially influence future energy-conserving vehicle design and use.

Imagine this: You and your family are on a road trip, driving halfway across the country. Maybe you're thinking about how much traffic is on the freeway, or where you'll stop for dinner. Periodically you think about how much gas you have left in your tank.

Now imagine your car runs on solar power. Before making your hotel reservation, you'll need to ask yourself questions such as these: How cloudy will it be today? When does the sun set this time of year? Can I stop for lunch now, or should I keep driving?

How you answer these questions could mean the difference between "Are we there yet?" and "Will we get there?" Making informed decisions will require knowledge about cloud cover, wind, road conditions, your car's capabilities, and the interlinking energy relationships. Radio weather forecasts, road maps, and car manuals provide only a small portion of this information and require effortful interpretation (Cotter, Roche, Storey, Schinkel, & Humphris, 1999). For vehicles powered by intermittent energy sources to be successfully adopted for personal and commercial use, further driver support will be required.

At the University of Toronto, the BlueSky Solar Car Racing team has been dealing with these challenges since 1997, competing in the equivalent of a solar "Formula One." Just as many cutting-edge motorsport technologies and designs have now been integrated into our everyday vehicles, cognitive support tools that win solar races in this decade could help the commuter of tomorrow race home for dinner in the next. In this article, we present excerpts from a prototype solar racing support tool developed for the BlueSky team, and outline how interface design can contribute to more sustainable vehicle technologies.

BlueSky Racing

BlueSky's first race car was simply built, weighed down with car batteries, and equipped with solar cells barely powerful enough to run a hair dryer. Its current vehicle sports a carbon-fiber body and features gallium arsenide solar cells, lithium-ion batteries, and high-efficiency motors that propel it to highway speeds. The team competes in long-distance races that span entire continents (Cotter et al., 1999).

To stand a chance of winning in a 100-strong race pack, BlueSky needs a reliable, state-of-the-art car. But when the clouds roll in, they need something less tangible: a winning strategy. For that, they turn to the crystal ball readers in their strategy team. The strategy team is a mobile pit crew that monitors the car's performance with telemetry data from its onboard sensor systems, keeps track of the competition, and maintains radio contact with the driver. The crewmembers also strategize, using their expertise to integrate data from weather reports, racecourse maps, and "home-brewed" car physics models. Through continuous refinements, they attempt to determine how fast the car should be driven throughout the race to safely cross the finish line with empty batteries and a record average speed.

The level of complexity and uncertainty in these decisions foils attempts at long-range planning. Exactly when and where a developing storm will cross the racecourse, and what actions the driver should take must be estimated and frequently reevaluated.

Design Problems and Processes

During their 10 years of racing, the BlueSky Solar Team's mechanical, electrical, and computer engineers have developed an assortment of documents, hardware, and software to support the strategy team's cognitive work. Solving technical challenges was the team's primary focus; applying human factors/ergonomics principles was a lower priority. However, as the technology of solar cars has matured, effective race strategy has emerged as a deciding factor in many victories.

A human-computer interface design project provided the opportunity to collaborate with the BlueSky team. We carried out an analysis over a three-month period, then designed and prototyped an integrated race strategy planning and monitoring interface. Because of the strong influence of physical processes on the solar car, the complexity of the strategy team's work, and the large amounts of data that they must integrate, we adopted a representation-aiding approach. The principles of representation aiding hold that task performance can be improved by using interfaces that provide a faithful representation of relevant real-world constraints in a form compatible with human perceptual and cognitive abilities (Bennett, Nagy, & Flach 2006). Specifically, we used the *ecological interface design* (EID) methodology (Burns & Hajdukiewicz, 2004), the most highly developed theoretical framework for representation aiding.

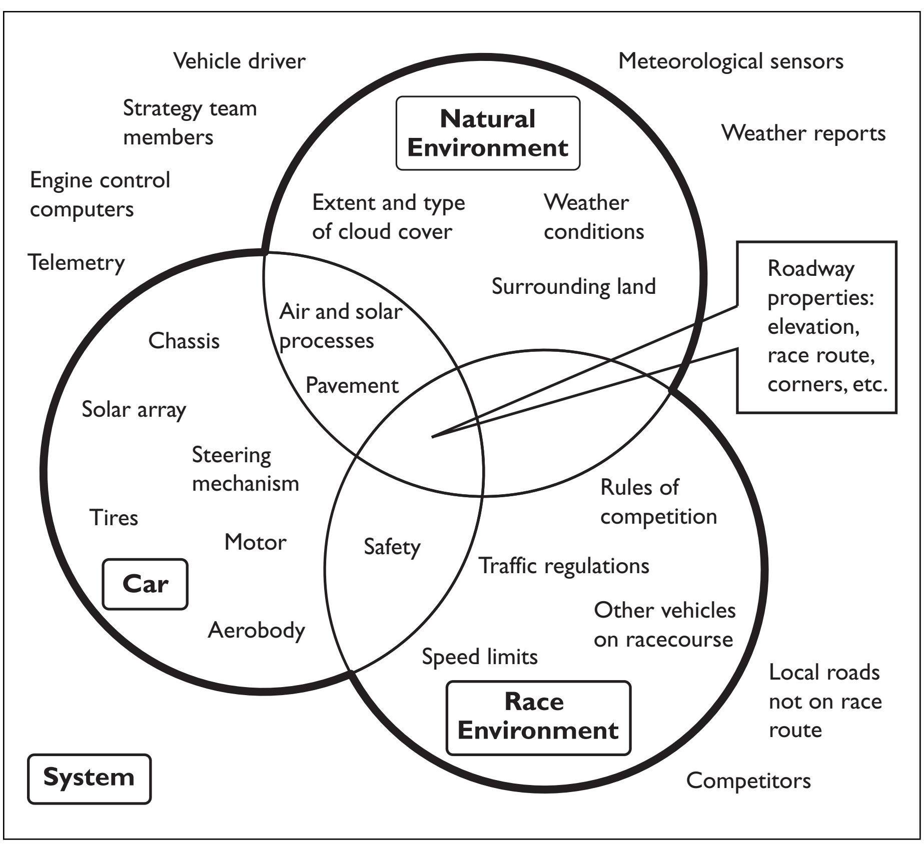

Figure 1. System and work domain boundaries.

FEATURE AT A GLANCE: Solar car racing is both a highly competitive sport and a test arena for tomorrow's renewable-energy applications. This article describes the design of a graphical interface for solar car race strategy planning. The coupling, unpredictability, and size of the solar car racing environment present tough challenges to racing strategy teams. Representation-aiding techniques provide a useful approach for managing this complexity, translating difficult problems into visual analogues that are better suited to human information processing.

KEYWORDS: driving, cognitive, ecological interface design, representation aiding, sustainability

In the first two weeks, we researched solar car racing through a literature review and interviews with team members. Unfortunately, the analysis occurred during a typical (i.e., cold, snowy, dark) Canadian winter, so naturalistic observations of the strategy team were not possible. Over the next month, we carried out a work analysis, developed the form and content of a series of paper prototype displays, and produced a design specification document. These were delivered to the solar car team for implementation.

Analysis Highlights

We began by analyzing the system in which solar car racing takes place. We identified the core elements of the system as the racecar itself, the natural environment, and the racing regulatory environment that constrains the legal actions of the race team. We defined the combination of these elements as the work domain, which is outlined in Figure 1. Items shown outside the Venn diagram are part of the system but were not considered in the work domain analysis (WDA). Although the system includes humans, automation, sensors, and interfaces, we followed an ecological approach (Vicente 1999) and considered these as elements to be influenced *by* the design process rather than as inputs *to* it (Burns & Hajdukiewicz, 2004). Existing team roles, training methods, and computer systems can be redesigned, whereas physical laws and legal constraints usually cannot.

Although our approach acknowledges human operators' cognitive and perceptual constraints, the aim is first to determine from the work domain what needs to be represented and then to develop visual representations that suit human abilities.

Dividing the work domain into three parts enabled us to explicitly consider physical divisions and conflicting functional purposes (Burns & Hajdukiewicz, 2004), as listed in

Excerpt from the Work Domain Analysis Showing Domain Subdivision

	Car's Area	Natural Environment Area	Race Environment Area
Functional purpose	Complete race safely in minimum possible time		Provide competition structure, ensure safety of persons on roadway
Abstract function	Conservation and transformation of energy, force balances	Conservation of energy and mass, entropy generation	Traffic laws, race regulations
Generalized function	Propulsion, regeneration, rolling friction, tire grip, etc.	Solar intensity, atmospheric transmissivity, wind, terrain, water processes	Allow traffic to cross paths, maintain fairness, etc.
Physical function	Capabilities of motor, tires, etc.	Sun, air, land, precipitation	Traffic lights, checkpoints, route path, etc.
Physical form	Motor winding air gap, tire tread thickness and composition, etc.	Solar radiation, wind speed and direction, landforms, precipitation intensity and location, etc.	Traffic light color status/cycle time, route and checkpoint location, etc.

the table above. Functional purposes indicate the reason the system was designed and form the highest, most abstract level of a WDA representation. Intermediate and lower levels indicate the domain at decreasing levels of abstraction. A complete WDA provides a functional representation of the work domain that is compatible with how humans manage complexity (Vicente, 1999).

To act effectively, the strategy team must respect constraints from multiple areas and levels of abstraction and weigh one against another. For example, speeding through a twisting section of wet road would raise the car's average speed, but at the possible expense of exceeding its safe maneuvering capability. What's more, this risky maneuver might lead the car directly under a patch of clouds that might otherwise have passed by before its arrival.

To accurately reason about the ever-changing race environment from a cramped bench seat in the chase van, strategy team members need sources from which they can extract the relevant information highlighted in the WDA.

Implications for Design

The results of our analysis informed the content, form, and structure of the interface. When determining content, we did not limit our design to existing data sources. For example, our analysis suggested that three-axis accelerometers and suspension travel gauges should be added to the solar car telemetry to provide essential data for energy and safety factors. Likewise, a satellite or wireless Internet connection could provide machine-readable weather and traffic forecasts. Physical laws and constraints were applied to derive information that was not directly measurable, such as energy flows and safety indications (Hilliard & Jamieson, 2007). Although it is likely that highly experienced team members may have considered some of these factors in the past, this would be expected to be effortful and error-prone.

In designing the visual forms, we adopted representational forms from instructional texts (e.g., Burns & Hajdukiewicz, 2004) whenever possible in order to make them compatible with user expectations. When required, we developed novel forms to convey domain constraints using design heuristics and principles of human perception.

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These forms were organized into four views according to areas and abstraction levels of the WDA: maintenance, energy, safety, and navigation. Principles of display proximity (Wickens & Carswell, 1995) and emergence (Bennett et al., 2006) were used to visually connect related forms within each view. The maintenance view represented the car's components in terms such as voltages, currents, and temperatures, corresponding to the generalized and physical function levels shown in the table. The energy view represented the balance and flow of energy identified at the abstract function level. The safety view included all elements related to the safety functional purpose of the solar car. The navigation view represented elements from the natural environment and race regulation areas of Figure 1 and related them to the solar car.

In the rest of this article we discuss three examples from these views that illustrate the representation-aiding approach.

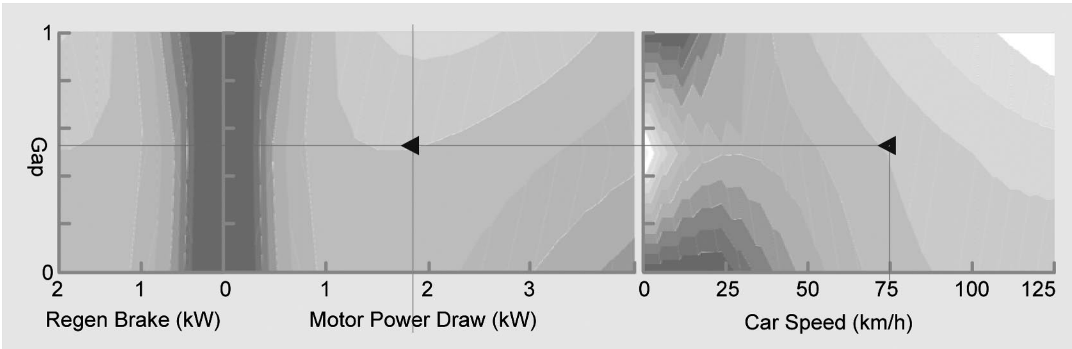

Figure 2. Motor efficiency map (from energy view). In the scenario depicted here, increasing the gap setting would move the triangles upward into the lightly shaded areas, representing higher motor electrical efficiency. The current gap is more appropriate for lower speeds, as shown by the horizontal linking line passing through the 25km/h mark's lightest contour. Motor efficiency is displayed numerically elsewhere in the view.

Motor efficiency map. The BlueSky race car is driven by a motor custom-built for solar racing. Instead of using a conventional gearbox, the driver manually adjusts the motor's rotor-stator air gap on the fly to optimize electrical efficiency. The strategy team's existing driver support tool was a set of graphs that plotted nominal motor efficiency on axes of power and speed, one graph for each gap setting tested. Determining the most appropriate gap for a given power or velocity meant interpolating between graphs, which imposed both a visual scanning and a working memory load on team members.

The new graphic form is displayed in Figure 2. To show continuous relationships between the motor's four variables, efficiency is plotted as contours on axes of gap, motor power, and car speed. Two plots are required to convey the four-dimensional relationship on the screen's two-dimensional surface. The current operating point is marked on both graphs and connected with a line to increase display proximity (Wickens & Carswell, 1995).

In this graphical representation, higher-efficiency gap settings for the car's current speed or power can be perceived as lighter contours above or below the current operating point, instead of requiring effortful cognitive interpolation between graphs. This graphic reveals the effects of the four-dimensional motor efficiency relationship: Changes in car speed are reflected in the shape of the power map, and vice versa.

By representing physical constraints in a visual form, this display can clearly indicate to the strategy team not only the most appropriate gap setting for the current conditions (to be radioed to the driver) but also the potential effects of changes in car speed or motor power caused by wind or road grade. A simplified version of this display could support a solar commuter in operating his or her car at its efficiency "sweet spot."

Car-handling map. The safety of the solar car depends on driver control of sideways forces acting on the car, either for maneuvering or to counteract wind disturbances. As suggested by a previous application of representation aiding to rally car racing (Kruit, Mulder, Amelink, & van Paasen, 2005), displaying constraints derived from a car-handling physics model may enable the strategy team to perform supervisory control of the car driver. In wet, windy driving conditions, offering the driver feedback about safe handling limits could save races – and lives. Currently, no such feedback mechanism exists.

The shaded area in Figure 3 represents the car's safe handling envelope, plotted on axes of speed and inverse corner

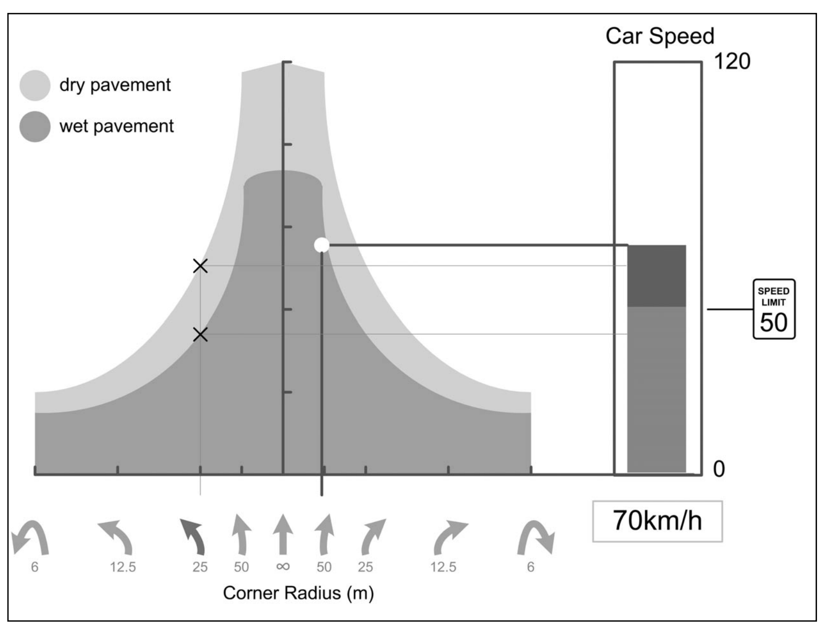

Figure 3. Car-handling map (from safety view). In this scenario, the navigation system has highlighted an upcoming left-hand curve and marked the corresponding point on the car's dry pavement handling envelope with an X. The car's current speed and cornering acceleration are plotted with a circle. Currently, the car is both exceeding the legal speed limit and traveling too quickly to negotiate the next corner safely.

radius. The shape of the envelope corresponds to physical constraints: Increasing speed decreases the severity of corners that can be safely navigated. The envelope shrinks as traction decreases, either through wet weather or from aerodynamic effects at high speed.

Because both the race route and the car's location are known, speed limits and upcoming corners can be incorporated into the graphical forms. If the car's speed exceeds legal or safe handling limits, high-salience colors draw attention to the danger. By making invisible constraints visible, this graphical form should help the strategy team more quickly evaluate the driver's cornering speeds and ensure both safety and maximum energy efficiency. If a sharp turn lies ahead, knowing the car's maximum safe cornering speed can guide a solar commuter in the efficient use of regenerative brakes, which convert kinetic energy into electrical energy.

Time-distance space. The most important information for the strategy team appears in the navigation view. It includes their main control: the planned speed profile of the car. Car velocity is the link between distance-based features such as hills and time-based features such as sunlight. Some features, such as cloud cover, challenge human predictive ability because they move and change shape chaotically, unlike regular solar cycles and immovable mountains. Avoiding cloud cover is a key factor in a successful race strategy.

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Our solution was to design several forms expressing the integrative relationship between speed and distance, as shown in Figure 4. The racecourse distance is plotted on the horizontal axis because the race route is fixed and can be considered one-dimensional. This provides context for the planned speed profile and distance-based constraints such as hills and speed limits. The time-distance space emerges below, with time of day on the vertical axis. By integrating the planned velocity profile, a line plotted across this space forms a visual analogy for the trajectory that the car follows through space and time as it completes the race. With computer-aided analysis of

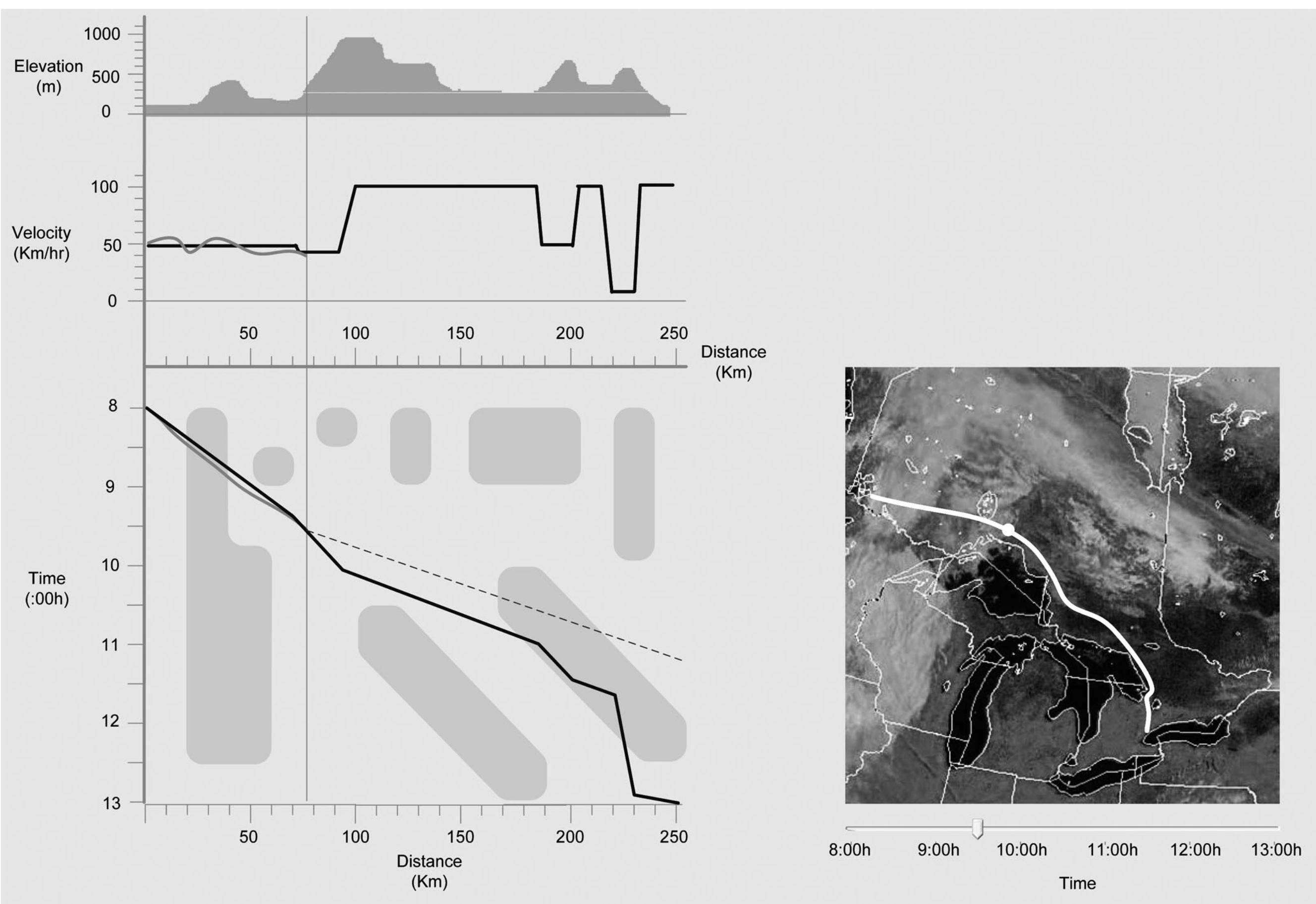

Figure 4. Time-distance space (from navigation view). In this scenario, the car is on schedule, and the team plans to accelerate to 100 km/h at the top of the next hill. Later in the day, two cloud systems will partly cover the race course between the 100-km and 250-km marks, leaving an hour-long moving "sun window" between them. The dashed line shows that it is too late to outrun the clouds, and the dark line shows that the current race plan will put the car under cloud cover from 11:00 a.m. to 12:00 noon. Slightly reducing vehicle speed at 10:30 might be a wise strategy.

weather forecast data, the projected effects of clouds along the racecourse can be mapped onto the time-distance space, shown by the shaded areas in Figure 4.

This graphical form clarifies the effect of small speed changes over long periods by translating a cognitive problem into a visual one. With reliable weather forecast data, the driver can avoid even large storm systems without drastic speed changes. For a solar commuter, this type of display could help to plan when to leave work: Depending on the weather, staying half an hour late might actually save you time.

Application and Other Domains

The BlueSky team accepted the design prototype and plans to implement it for the 2008 racing season. The representation-aided display is expected to decrease monitoring latency, increase accuracy of fault diagnoses, and free cognitive resources for planning. This project highlights several promising ideas for supporting successful solar-powered vehicle operation, and adapting these concepts for direct use by drivers is an opportunity for future research.

The Toyota Prius's energy displays provide one example of the successful introduction of a simple driver efficiency support tool. More active contextual advice systems have been shown to reduce fuel consumption in conventional vehicles by 14% (Van Der Voort, Dougherty, & Van Maarseveen 2001). Experts can push the boundaries further. Hobbyist "hypermilers" have developed driving techniques that can boost mileage by 50% in everyday use. The world record for an unmodified Prius is 110 mpg, more than twice its EPA rating! This level of driving performance requires deep knowledge of vehicle dynamics and energy relations; it is perhaps no coincidence that the world champion of fuel economy, Wayne Gerdes, is a nuclear power plant operator (Gaffney, 2007).

As human factors/ergonomics designers and researchers, we seek to design systems that enable novice users to exhibit expert behavior. The demonstrated benefits of representation aiding in this regard (Bennett et al., 2006) may also apply in the driving domain. The first such graphical driver support tools are being evaluated and have shown promising results, improving performance while reducing task demands (Seppelt & Lee, 2007).

Some of the graphical forms developed in this project may be useful in other domains. For example, the time-distance graphic is broadly applicable to travel on preplanned routes with space- and time-dependent features. It may be useful for coordinating high levels of utilization of rail transport systems (as a dynamic variant of E. J. Marey's [1878] train schedule), for ?eld planning of military movements exposed to enemy surveillance, or for navigation of large marine vessels in restricted waterways.

The BlueSky Solar Racing team's depth of analysis is unnecessary for today's gas-fueled commuters. But as energy costs increase and low-carbon solutions become increasingly necessary, people will have to change their habits and adapt to the energy sources available to them. Finding ways to support nontechnical users in successfully employing more sustainable, lower-power, and more complex energy sources is essential for technological success and commercial adoption. After all, to paraphrase Lund (1996), if alternative energy systems don't work for people, they don't work.

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Antony Hilliard received his M.ASc. in industrial engineering in 2007 and is a Ph.D. student at the University of Toronto. His professional experience includes process, mechanical, and marine design. Through contributions to the development of low-carbon transportation and renewable energy programs on campus, he hopes to pursue further research into the human factors of sustainability.

Greg A. Jamieson is an associate professor of mechanical and industrial engineering at the University of Toronto. His research and teaching center on the design of cognitive artifacts for people working in complex systems. He specializes in human-automation interaction and human-machine interface design with applications primarily in process control. He may be reached at 5 King's College Rd., Toronto, ON, M5S 3G8, Canada, +1-416-946-8504 or jamieson@mie.utoronto.ca

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