in this area, seven separate simulator studies had been performed prior to 1999 (Ward & Dye, 1999).

Some types of investigation, by their very nature, almost have to be carried out on a simulator. Studies of the impact of illicit drug use fall into this category: It would be unethical and illegal to perform a real-world experiment of the impact of a substance whose use prior to driving is banned. Also, there could be ethical issues with an on-road study of sleep-deprived individuals. Similarly, research on the impact of cognitive impairment, such as caused by Alzheimer's disease, can be and has been carried out on a simulator (Rizzo, McGehee, Dawson, & Anderson, 2001).

Thus, one of the major motivations for using a simulator is that of health and safety: Experiments that would be difficult to carry out in the real world for ethical reasons can be performed in the risk-free environment of a simulator. Driver awareness of and response to risky situations, near crashes, and even real crashes (McGehee & Carsten, 2010) can be investigated in a simulator. Drivers can be subjected to levels of primary task demand and/or secondary task distraction that could not be investigated in real-world conditions or could only be investigated in the depleted and unnatural environment of a test track. In addition, driver ability to cope with vehicle or electronic system failure can be studied (Jamson, Whiffin, & Burchill, 2007).

Researchers can be provided with a huge range of data from a simulator. Essentially, the "vehicle" can provide the full variety of data that would be provided by a real-world instrumented vehicle—steering data, pedal data, engine data, and so on—as well as data about how the vehicle relates to the road environment, such as precise position. From position, recorded for example at 60 Hz, it is possible to derive speed, acceleration, variation of lateral position, lane position, position relative to other objects and vehicles in the virtual world (and hence time headway, time to collision, etc.), as well as vehicle handling information (friction and lateral g). Driver head and eye movements can be monitored and recorded, as can a whole suite of physiological information, such as data from electroencephalograms and electrocardiograms. All these types of objective data can be supplemented with subjective data on workload, acceptance, trust, behavioral intention, and so on. This potential wealth of data necessarily brings with it the responsibility for the researcher to identify important research questions and hypotheses in advance and to ensure that participants are not overloaded with questionnaires and protocols. It is normal to carry out a data reduction process on the raw objective data to prepare them for analysis in a statistical package. However, the simulator raw data should be fully archived so that further data reduction or calculation can subsequently be carried out.

Researchers also need to be aware that there are limitations to studies carried out on a simulator. One important issue relates to validity and concerns the motivation of participants in a simulator study. Participants will never be fully motivated in the way that they are in real-world driving. They are potentially aware (although they may be oblivious) of being observed, and they may not feel the same time pressure that they would when, for example, delayed by congestion in real traffic. Participants may be motivated to "obey" the experiment, resulting in compliance bias, or they may believe that in an artificial environment they are free from the normal constraints imposed by driving laws and norms. It is difficult to investigate the impact of these factors, so one must generalize and conclude that since simulator driving tends to reproduce the patterns of real-world driving—so that, for example, young males drive in a more risky manner than other groups—the data obtained can be considered sufficiently reliable.

It also has to be accepted that there are inherent limitations to the scope of simulator studies. One such limitation is a restriction on investigating learning effects using a within-participant experimental design. Even with repeat visits (and these are often quite difficult to arrange), it is not possible for an individual to accumulate extensive experience of a new road feature or a new electronic system from a few hours of driving in a simulator. Learning and adaptation effects can be studied. Thus, Jamson, Lai, Jamson, Horrobin, and Carsten (2008) examined the persistence of road engineering treatments for speed management by designing an experiment with repeated exposure to each treatment. But investigating the implications of a few repeats of exposure to a treatment is not equivalent to a study of long-term acclimatization to a treatment. For that purpose, driving simulators are ineffective except perhaps as an adjunct to real-world exposure.

4. TO MOVE OR NOT

Perhaps the most hotly debated area of simulator design is that of motion—how desirable it is and, if it is provided, what type of motion platform should be employed. Cost is a major consideration: Provision of motion substantially increases the cost of establishing a simulator, with a consequent effect on operating costs. It is difficult to argue against the desirability of motion, and various validation studies have shown that driving behavior becomes more life-like with the provision of motion feedback. Thus, Alm (1995) found that, with the motion system of the VTI simulator enabled, drivers were able to drive a more steady course on curves than when the motion system was disabled.

Similar effects of a motion system on lateral control have been found in other studies. Greenberg, Artz, and Cathey (2003) used a hexapod with and without motion cueing. In one experiment, drivers were administered a number of secondary tasks. With handheld tasks (but not