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WHOLE-BODY OSCILLATORY MOTION AND ROAD-TRANSPORT INNOVATIONS: A HUMAN-FACTORS-AND-ERGONOMICS PERSPECTIVE WITHIN A RIDE-QUALITY FRAMEWORK

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Abstract

In the belief that the field of study of human responses to whole-body oscillatory motion falls within the ambit of human factors and ergonomics, a human-factors-and-ergonomics perspective is adopted here in an attempt to recognise some possible applicative reverberations of expected road-transport innovations. The need for a general framework taking into account ‘soft’ and ‘hard’ features as well as ‘subjective’ and ‘objective’ implications is identified. The comprehensive concept of ride quality is suggested as a good candidate to cope with the complexity of the open problems.

1. A paradigm shift?

The world of *road transport* has been rapidly metamorphosing in recent years. Meanwhile, academic scholars, management consultants, and business executives have been discussing whether and when a paradigm shift is to take place [Corwin *et al.*, 2016; Hannon *et al.*, 2016; Fulton *et al.*, 2017; Attias, 2017a]. *Electrification*, *connection*, *automation*, and *sharing* are the keywords for next-generation road vehicles. The related processes of innovation originated at different times and, guided by different needs, developed in different ways before starting to converge.

Despite the many technical, technological, economic, ethical, social, cultural, political, and regulative *challenges* to be faced [Boulanger *et al.*, 2011; Lu *et al*., 2014; Bagloee *et al.*, 2016; Anderson *et al.*, 2016; Litman, 2017], *major advances* are expected within the automotive industry, together with the creation of new opportunities and with the modification of value chains and business models [Maitland and Guttmann, 2014; KPMG, 2015; Fournier, 2017].

The ‘hype’ in the media and the speculation amongst insiders have reached incredible peaks; nevertheless, possible developments are not very clear and it is still a matter of discussion whether the nature of such processes of innovation will prove to be *disruptive* and *revolutionary* or rather *incremental* and *evolutionary* [Jiang *et al.*, 2015; Attias, 2017b]. However, the changes on the horizon may be so significant for the world of road transport to make a paradigm shift possible and a structured approach necessary from all the relevant points of view.

In the belief that the field of study of human responses to whole-body oscillatory motion falls within the ambit of human factors and ergonomics, a human-factors-and-ergonomics perspective is adopted here in an attempt to recognise some possible applicative reverberations of expected road-transport innovations. The need for a general framework taking into account ‘soft’ and ‘hard’ features as well as ‘subjective’ and ‘objective’ implications is identified. The comprehensive concept of ride quality is suggested as a good candidate to cope with the complexity of the open problems.

2. Electrification, connection, automation, and sharing

Amongst the ongoing processes of innovation, *electrification* was almost certainly the first to be conceived, discussed, and put into practice. Despite the first prototypes dating back to the 1820s, electric propulsion reached its heyday only in the early 1900s by virtue of the advantages brought over fuel propulsion in terms of power, startability, and controllability [Brinkman *et al.*, 2012; Matulka, 2014]. After a decline in the 1920s, a renaissance had to wait until the energy crisis of the 1970s and the emergence of the idea of *sustainable transport* in the 1980s, when the need to diversify energy sources, to moderate resource consumption, to reduce air-pollutant emissions, and, later, to oppose climate change started to gain momentum in public opinion as well as in academic, political, and industrial environments [Brinkman *et al.*, 2012; Matulka, 2014]. Eventually, during the 1990s and the 2000s, the development of automotive electronics and the hybridisation of propulsion systems led to a proliferation of *electric vehicles* (*EVs*), which, with respect to electrical grids, may be totally dependent, as in the case *of battery electric vehicles* (*BEVs*), totally independent, as in the case of *hybrid electric vehicles* (*HEVs*), or partially dependent, as in the case of *plug-in hybrid electric vehicles* (*PHEVs*) [Kumar and Jain, 2014]. In the future, electric vehicles are expected to integrate with *smart grids* [Mwasilu *et al.*, 2014] consisting of energy-distribution infrastructures evolved so as to become physical substrates for bidirectional information exchange and notably so as to perform some of the functions of communication, control, and management needed to implement other processes of innovation.

Connected and autonomous vehicles (*CAVs*) [Bimbraw, 2015; Bell *et al*., 2016; McCarthy *et al*., 2016; SMMT, 2017] are *driving automation systems*, of five different standardised levels of driving automation [SAE International, 2016], that are integrated in ‘ecosystems’ known as *Internet of Things* (*IoT*) and more specifically as *Internet of Vehicles* (*IoV*) [Yang *et al*., 2014; Lengton *et al*., 2015], and that exchange information with any entity that may affect them through vehicular communication systems known as *vehicle-to-everything* (*V2X*) and more specifically as *vehicle-to-vehicle* (*V2V*) and *vehicle-to-infrastructure* (*V2I*) [Sprouffske, 2013]. In fact, there is no uniformity of views on the eventual convergence between the processes of connection and automation, nor is it clear whether connected and autonomous vehicles may be part of future *Intelligent Transport Systems* (*ITS*) [Directive 2010/40/EU of the European Parliament and of the Council, 2010; Zmud *et al.*, 2015]; however, connected and autonomous vehicles, ideally to be deployed within ‘archipelagos’ of sustainable, functional, and networked *smart cities* [Geoffron, 2017], are expected to change significantly not only the *ride experience*, but also the *urban environment* [Cuddy *et al*., 2014].

From a socio-economic point of view, the controversial transition from a product-oriented *traditional economy*, based on individual ownership, to a service-oriented *sharing economy*, based on collective access, has been giving rise to momentous social changes in most countries [Puschmann and Alt, 2016; Frenken and Schor, 2017]. While habitually clear distinctions have been fading, be they between manufacturers and consumers of products or between suppliers and users of services, evolving lifestyle and values scale of today's young adults have been redefining, perhaps irreversibly, the very concepts of consumption and use as interpreted by the *millennial* generation [Godelnik, 2017].

Shared mobility, driven by economic and environmental factors [Böcker and Meelen, 2017], is probably the most vital and rapidly evolving expression of sharing economy [Feigon and Murphy, 2016; International Transport Forum, 2016]. Within the epoch of *liquid modernity*, in which some descry "the growing conviction that change is *the only* permanence, and uncertainty *the only* certainty" [Bauman, 2012, p. viii], road vehicles tend to be seen less and less as status symbols [Adam, 2015], let alone as totemic representations of individual freedom [D'Costa, 2013], and more and more as *mobility tools* [Attias, 2017a]. In fact, exercise of individual freedom may progressively result in people just not wanting or even not being able at all to drive, taking advantage, by preference, of the attractive flexibility offered by a plethora of new opportunities such as *car-sharing*, *microtransit*, *ride-sharing*, *ride-sourcing*, and *ride-splitting* [Feigon and Murphy, 2016]. Interestingly, some even deem possible that driving automation systems allow alternative travel suppliers to acquire market shares at the expense of established short-range terrestrial and aerial competitors [Fairs, 2015; Hazan *et al.*, 2016].

Despite the enthusiasm palpable in some environments, it is spreading the view that, in the long term, electrification, connection, automation, and sharing can be sustainable and beneficial only if implemented together [Hannon *et al.*, 2016; Fulton *et al.*, 2017]. In particular, considering that private road vehicles are characterised by very low average values of occupancy rate (of the order of 1.5 persons per vehicle in the United Kingdom in the years from 2004 to 2008 [European Environment Agency, 2010]) and by very high average values of idle time (approximately 96 % of the total time in the United Kingdom in the years from 2002 to 2008 [Bates and Leibling, 2012]), widespread adoption of connected and autonomous vehicles is deemed by some to be sustainable only in a road-transport scenario dominated by shared electric mobility [Schonberger and Gutmann, 2013; Offer, 2015].

Summarising with the effective words of Attias [2017a, p. 17],

> The traditional concept of a powerful, personal car is being replaced by other types of mobility. The social symbols, priorities and preferences of young people are no longer the same. Real-time access to information has become essential. Mobility is more important than power. People want to remain constantly connected to their environment. Cars can no longer be considered as an end in themselves, but as tools for gaining mobility. These new services contribute to the arrival of new types of mobility that are more relaxed, rational and sustainable, and to the emergence of a new ecosystem.

3. A human-factors-and-ergonomics perspective

Should electric, connected, autonomous, and shared road vehicles become the norm, significant *behavioural changes* would be to expect amongst users [Jamson *et al.*, 2013; Trommer *et al.*, 2016].

As well as air pollutants, *noise and vibration* would be emitted to a lesser extent by electric powertrains than by conventional powertrains. However, as an undesirable effect, otherwise overshadowed noise and vibration might emerge as a result of a 'draining of the swamp' [Goetchius, 2011] and, paradoxically, become a bigger issue for road-vehicle users who might have, especially in this respect, higher expectations about electric vehicles.

Being more often *passengers rather than drivers*, road-vehicle users might engage in *new (on-board) activities* and a more productive, enjoyable, and relaxing use of time would be possible; work, entertainment, socialisation, and even relaxation would increasingly enter ride experience, providing new opportunities of human-machine and human-human interaction [Laurier and Dant, 2011].

For traffic flows to be manageable and for new (on-board) activities to be practicable, *new (autonomous) driving styles* would become prominent: average speed values would be lower, lane changes would be less frequent, and vehicle paths would be optimised [Jamson *et al.*, 2013; Le Vine *et al.*, 2015; Elbanhawi *et al.*, 2015]. As a result, within the classic compromise between *performance* and *comfort*, the balance point would shift towards the latter.

Adopting a human-factors-and-ergonomics perspective, new (on-board) activities and new (autonomous) driving styles would imply *new motion environments* and *new seating configurations* to be taken into account [van Veen *et al.*, 2014; Ive *et al.*, 2015], as well as *new issues* to be addressed, especially in terms of situational awareness, activity interference, and motion sickness [Sivak and Schoettle, 2015; Cunningham and Regan, 2015; Kyriakidis *et al.*, 2017].

In order to meet *vehicle habitability* needs that are appropriate to the contemplated road-transport scenario, significant advances in *vehicle interiors* and, more specifically, in *vehicle seats* are to be pursued. Indeed, interest in the topic is growing rapidly within academic and industrial communities, to the point that specialised symposia are now organised [Uki Media & Events, 2017]; moreover, some insiders even predict that exterior design is to lose importance to the benefit of interior design [Fell, 2017]. Ultimately, if vehicle interiors become living spaces alongside home and office, improving ride experience as a whole may well pass through creating what marketing enthusiasts have already started to promote as *seating experience* [Rychel, 2016; Wysocky, 2016; Dobrian, 2016].

4. Ride quality and comfort

As a norm, *customer satisfaction* is the explicit or implicit basis of business models, both as a starting point (motivation) and as an end point (objective). International Standard ISO 9000:2015 formally defines *customer satisfaction* as the “customer’s perception of the degree to which the customer’s expectations have been fulfilled” [International Organization for Standardization, 2015]. In a road-transport scenario in which comfort is valued more than performance, it is reasonable to expect that ride experience may be strongly affected by human-factors-and-ergonomics issues. Stated otherwise, to fulfil *customer expectations* at the core of customer satisfaction, it may be necessary to provide future road-vehicle users with higher degrees of *ride quality*.

In the context of *automotive engineering*, the expressions *primary ride*, *secondary ride* (or *shake*), and *harshness* normally refer to oscillatory motion of the sprung mass of a vehicle respectively in the ‘lower’ frequency range (up to 5 Hz), in the ‘intermediate’ frequency range (between 5 Hz and 30 Hz), and in the ‘higher’ frequency range (between 30 Hz and 100 Hz) [SAE International, 2008].

However, in the context of *human responses to oscillatory motion*, the term *ride* normally refers to the “measurable motion environment (including vibration, shock, translational and rotational accelerations) as experienced by people in or on a vehicle” [International Organization for Standardization, 1997b].

On this basis, International Standard ISO 5805:1997 defines the derived concept of *ride quality* as the “degree to which the whole subjective experience (including the motion environment and associated factors) of a journey or ensemble of journeys by vehicle is perceived and rated as favourable or unfavourable by passengers or operators” [International Organization for Standardization, 1997b].

In the specified context, the expression *ride quality* has been in use for several decades essentially with reference to the sole *motion environment* [Green, 2012]; nevertheless, with the aforementioned standardised definition, it assumes an extremely broader meaning. While *(dynamic sitting) comfort* can be understood, with reference to the sole motion environment, as the “subjective state of well-being or absence of mechanical disturbance in relation to the induced environment (mechanical vibration or repetitive shock)” [International Organization for Standardization, 1997b], ride quality is to be regarded as a complex *psychophysical percept* reflecting the *whole subjective experience* and integrating many subjective human responses related not only to dynamic sitting comfort, but also, inter alia, to *static sitting comfort*, *acoustic comfort*, *visual comfort*, *thermal comfort*, and *olfactory comfort* [International Organization for Standardization, 2006]. Furthermore, one should not ignore the contribution of ‘soft’ *affective/emotional features* (as opposed to ‘hard’ *functional/ergonomic features*) that are linked to consumers’ feeling and image of products and that are also referred to by means of the multifaceted Japanese word *kansei* [Tanoue *et al.*, 1997].

To summarise, ride quality may be regarded as a standardised and measurable counterpart of some undefined and undetermined idea of overall ‘ride feeling’. Starting from the 1980s, customer expectations in terms of ride quality have grown so significantly within the automotive market that new *noise, vibration, and harshness* (*NVH*) departments have been created by most manufacturers in order to conduct specialised research and development focussing on acoustic comfort and dynamic sitting comfort [Mansfield, 2005]. More generally, approaches taking into account a greater number of possibly influential factors should be attempted in order to understand the relative importance and the interactions of the various factors [Oborne, 1978].

That being said, it is not entirely clear what *comfort* actually is from a psychophysical point of view, nor what relations subsist between comfort and its alleged opposite *discomfort*; in particular, it is still unknown whether comfort and discomfort can be understood one as absence of the other or, alternatively, they should be regarded as distinct, possibly multidimensional, psychophysical percepts [Zhang *et al.*, 1996; de Looze *et al.*, 2003]. Besides, although standardised definitions can provide useful reference and help to limit misunderstandings in practical situations, relying too much on them may result in overrating current knowledge.

Beyond the psychological and philosophical disputes on the semantic value of the word comfort, it is well recognised that *sitting comfort*, both static and dynamic, plays a key role in the wider context of ride quality [Ebe and Griffin, 2000; Mansfield, 2013]. Specifically, at least in static sitting conditions, correlations are known between the subjective well-being and the *surface distribution of contact actions at the seat-occupant interface* [de Looze *et al.*, 2003; Hiemstra-van Mastrigt *et al.*, 2017]; however, in order to cope satisfactorily with the study of sitting comfort for road-transport applications, structured approaches may be needed to take into account all the potentially influential factors [Kolich, 2008; da Silva *et al.*, 2012].

5. Comfort and protection

Modern road vehicles are parts of very complex human-machine systems whose conception and design benefit from a human-oriented approach taking into account, amongst others, requirements of *comfort* and *protection* [Braess and Reichart, 1990]. Nevertheless, within research and development environments, comfort and protection issues have been habitually addressed by applied scientists and engineers who are active in the different and rarely interacting communities of *human factors and ergonomics* and of *vehicle safety*; in fact, comfort and protection do overlap. By way of example, it is now acknowledged that the design of vehicle seats has implications in terms of both comfort and protection. On the one hand, while not being reducible to this, vehicle seats can be regarded as *occupant restraint systems* with full rights [Adomeit, 1979]; on the other hand, ergonomically designed vehicle seats are likely to allow road-vehicle users to stay in better, and ultimately safer, conditions.

According to International Standard ISO 7862:2004, an *occupant restraint system* is an “arrangement of components which is intended to diminish the risk of injury to the occupant in the event of a vehicle collision by controlling the occupant displacement and acceleration” [International Organization for Standardization, 2004]; as opposed to *active safety systems*, which reduce the risk of injury by reducing the probability of occurrence of the injury, occupant restraint systems are usually regarded as *passive safety systems*, which reduce the risk of injury by reducing the severity of the injury.

With the advent of next-generation road vehicles, the traditional distinction between active and passive safety systems is likely to become less and less clear [Class *et al.*, 2013; ZF TRW, 2016; van Ratingen *et al.*, 2016]; moreover, in a road-transport scenario in which new (on-board) activities may result in increased interaction with human occupants, the role of occupant restraint systems is likely to become even more relevant. Two guiding principles have already been implemented in *advanced restraint systems*, notably *adjustability* (capability of accommodating human occupants having different anthropometric properties and taking different body postures) and *predictivity* (capability of being activated early and reversibly using data from environmental sensors, such as radars or cameras, or from active safety systems, such as the electronic stability control and the emergency brake assist); one more guiding principle, *adaptability* (capability of accommodating human occupants performing different on-board activities and experiencing different motion environments), is suggested here as worthy of attention.

It is not easy to make predictions about the impact that next-generation road vehicles may have on vehicle safety, especially in terms of risk of injury. On the one hand, lower values of average speed, less frequent lane changes, and optimised vehicle paths should have a beneficial effect. On the other hand, *situational awareness* and *out of position* may become major concerns; indeed, the very concept of out of position will probably need redefinition. It is worth noting that, at present, vehicle-safety issues of next-generation road vehicles seem to have been investigated focussing more on possible collisions due to errors in traffic-flow management than on human-factors-and-ergonomics implications.

In addition to vehicle seats themselves, occupant restraint systems in use include safety belts, safety harnesses, airbags, knee bolsters, padded dashboards, collapsible steering columns, laminated windshields, cargo barriers, anti-intrusion bars, safety cells, and crumple zones [Snyder, 1969; States, 1988]. Amongst all these, *safety belts* and *safety harnesses* are the only ones in continuous and close contact with seated human occupants of road vehicles. By fulfilling functions of *primary* (as opposed to *secondary* or *supplemental*) occupant restraint systems, safety belts and safety harnesses have been shown for decades to be key for the sake of vehicle safety [Hodson-Walker, 1970; Johannessen, 1984; Road Safety Observatory, 2013]. Indeed, the necessity of safety belts and safety harnesses is questioned rather seldom [Adams, 2007; Allsop *et al.*, 2008], and their use has long since been mandatory by law in many countries of the world [Weiss *et al.*, 2006] and in a wide range of situations [Glassbrenner *et al.*, 2004]. Understandably, vehicle safety implications of safety belts and safety harnesses have been investigated quite extensively [Huston, 2001]. Conversely, human-factors-and-ergonomics implications have been considered relatively seldom and, however, more from a *static* point of view [Dejeammes *et al.*, 1984; Balci *et al.*, 2001; Chen *et al.*, 2003] than from a *dynamic* point of view [Wyllie and Griffin, 2007, 2009; Zhao and Schindler, 2014].

6. The need for a general framework

The field of study of *human responses to whole-body oscillatory motion* is highly multidisciplinary in nature; indeed, it integrates knowledge and skills from several domains including engineering, industrial design, anthropometry, biomechanics, physiology, medicine, and psychology [Griffin, 1990]. Because of this manifold character, advocated is here the appropriateness of considering it within the ambit of *human factors and ergonomics*, which seems to provide a cultural substrate wide enough to allow taking into account ‘soft’ and ‘hard’ features as well as ‘subjective’ and ‘objective’ implications.

Human responses to whole-body oscillatory motion in the context of road-transport applications aroused some research interest already in the early 1930s [Hirshfield, 1933]. However, as can be shown through a targeted search-result analysis within the *Scopus* bibliographic database, the topic emerged of its pioneering niche only in the 1960s. Eventually, it was in the 1990s that the number of related publications started to increase significantly.

In the light of the knowledge gained since the early years, widely recognised is by now the importance of understanding the relations between *subjective human responses* (dependent on individuals’ judgement) and *objective human responses* (independent of individuals’ judgement) to whole-body oscillatory motion. Nevertheless, despite the conspicuous amount of research already conducted, still many questions remain to be answered [Sandover, 1986; Griffin, 1990; Gierke, 1997; Mansfield, 2005; Brammer and Peterson, 2009].

From an industrial point of view, careful conception and design of vehicle seats have proved decisive for road-vehicle users, be they drivers or passengers, to be provided with ‘adequate’ *ride quality* not only in terms of *comfort*, *protection*, and other ‘hard’ *functional/ergonomic features*, but also of in terms of several ‘soft’ *affective/emotional features*. Indeed, pertinent *design guidelines* [Huston and Genaidy, 1997] and *technical standards* [British Standards Institution, 1987; International Organization for

Standardization, 1997a, 2004, 2016] do exist; however, new and updated ones need to be developed, ideally on scientific rather than on heuristic grounds.

It is well known that the characteristics of vehicle seats have a significant influence on both subjective human responses and objective human responses to whole-body oscillatory motion [Griffin, 1990]. Indeed, vehicle seat and human occupant together form a *seat-occupant system* that can and often should be regarded as a whole. The hypothesis is here advanced that, more generally, the *seat-occupant-restraint system* may need to be regarded as a whole.

Ultimately, in order to bridge the gap between *subjective human responses* and *objective human responses*, a *general framework* for the study of human responses to whole-body oscillatory motion may need to be considered within the ambit of *human factors and ergonomics*. In the specific case of road-transport applications, and especially in expectation of next-generation road vehicles, it may be appropriate to focus on the comprehensive concept of *ride quality* taking into account human responses related not only to *comfort*, *protection*, and other 'hard' *functional/ergonomic features*, but also to several 'soft' *affective/emotional features*. Within this framework, the *seat-occupant-restraint system* may need to be regarded as a whole.

7. A synthetic glimpse

The world of road transport has been rapidly metamorphosing in recent years. Despite the many challenges to be faced, major advances are expected within the automotive industry. Electrification, connection, automation, and sharing are the keywords for next-generation road vehicles. Although it is still a matter of discussion whether the nature of such processes of innovation will prove to be disruptive and revolutionary or rather incremental and evolutionary, the changes on the horizon may be so significant to make a paradigm shift possible.

Should electric, connected, autonomous, and shared road vehicles become the norm, significant behavioural changes would be to expect. Being more often passengers rather than drivers, road-vehicle users might engage in new (on-board) activities. New (autonomous) driving styles would become prominent and, within the classic compromise between performance and comfort, the balance point would shift towards the latter. Adopting a human-factors-and-ergonomics perspective, new (on-board) activities and new (autonomous) driving styles would imply new motion environments and new seating configurations to be taken into account, as well as new issues to be addressed. Accordingly, significant advances in vehicle interiors and, more specifically, in vehicle seats are to be pursued.

In a road-transport scenario in which comfort is valued more than performance, to fulfil customer expectations at the core of customer satisfaction it may be necessary to provide road-vehicle users with higher degrees of ride quality. Ride quality is to be regarded as a complex psychophysical percept reflecting the whole subjective experience or, in other words, as a standardised and measurable counterpart of some undefined and undetermined idea of overall 'ride feeling'. While emphasising that one should not ignore the contribution of 'soft' affective/emotional features (as opposed to 'hard' functional/ergonomic features), it is well recognised that sitting comfort, both static and dynamic, plays a key role in the wider context of ride quality.

Comfort and protection issues have been habitually addressed by applied scientists and engineers who are active in the different and rarely interacting communities of human factors and ergonomics and of vehicle safety; in fact, comfort and protection do overlap. Moreover, in a road-transport scenario in which new (on-board) activities may result in increased interaction with human occupants, the role of occupant restraint systems is likely to become even more relevant. Two guiding principles have already been implemented in advanced restraint systems, notably adjustability and predictivity; one more guiding principle, adaptability, is suggested here as worthy of attention.

In order to bridge the gap between subjective human responses and objective human responses, a general framework for the study of human responses to whole-body oscillatory motion may need to be considered within the ambit of human factors and ergonomics. In the specific case of road-transport applications, and especially in expectation of next-generation road vehicles, it may be appropriate to focus on the comprehensive concept of ride quality taking into account human responses related not only to comfort, protection, and other 'hard' functional/ergonomic features, but also to several 'soft' affective/emotional features. Within this framework, the seat-occupant-restraint system may need to be regarded as a whole.

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