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Review Article

Automotive Technology and Human Factors Research: Past, Present, and Future

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This paper reviews the history of automotive technology development and human factors research, largely by decade, since the inception of the automobile. The human factors aspects were classified into primary driving task aspects (controls, displays, and visibility), driver workspace (seating and packaging, vibration, comfort, and climate), driver's condition (fatigue and impairment), crash injury, advanced driver-assistance systems, external communication access, and driving behavior. For each era, the paper describes the SAE and ISO standards developed, the major organizations and conferences established, the major news stories affecting vehicle safety, and the general social context. The paper ends with a discussion of what can be learned from this historical review and the major issues to be addressed. A major contribution of this paper is more than 180 references that represent the foundation of automotive human factors, which should be considered core knowledge and should be familiar to those in the profession.

1. Introduction

In many fields of technology, examinations of the past can provide insights into the future. This paper examines (1) the driver- and passenger-related technology that was developed as a function of time and (2) the research necessary for those developments, as they affected both vehicle design and evaluation. This paper also examines how those developments were influenced by (1) advances in basic technology, (2) requirements from government agencies and international standards, and (3) even the news media. All of this is done roughly chronologically, with developments grouped into three time periods—before World War II, after World War II until 1989, and since 1990.

In the history of research, a research topic becomes popular at some time because of a societal need, researcher interest, technology trends, the introduction of a new method, or a new theory. As a consequence, the number of researchers in the field grows, as does the number of publications, which in turn leads to products, services, and new ideas. These factors have certainly affected the growth of the human factors profession.

The history of automotive technology and human factors research can be viewed similarly. Its history can be divided into three periods. They are (1) the decades before World War II (Section 2), (2) World War II until 1989 (Section 3), and (3) 1990 and beyond (Section 4). This last period is continuing, so it is a bit more difficult to be retrospective in grouping decades. Therefore, Section 4 is divided by research topics, not by decades. For each topic, research activities are described chronologically to help readers to understand how the research has progressed for these 20 years to reach the current status.

2. A Short History of Human Factors Aspects of Automotive Technology before World War II

2.1. Early Stage of Automobiles (1886–1919). Over the course of the first half-century after the invention of the automobile

(a) (b)

Figure 1: Tiller (Oldsmobile 1902 (a)) and bar handle (Peugeot Type 24 1899 (b)) (the author's (MA) photo collection).

by Karl Benz in 1886, various changes were made to self-powered vehicles so they were better suited to human abilities, changes based on experience with animal-drawn vehicles. Interestingly, the seatbelt had been introduced for steam-powered horseless carriages in the 1800s, but its purpose was to keep passengers on their seat, not to keep them safe in the event of a collision [1]. The steering mechanism in very early automobiles was a tiller, a lever arm that connected to the pivot point of the front wheels, a design derived from small boats. Tillers were easy to use for very slow speeds and lightweight vehicles (such as those with three wheels). However, steering a jolting tiller with sheer muscle power was difficult for heavy four-wheel vehicles moving at high speed. A bar handle with grips at both ends to be held with both hands was introduced that could be held more firmly than the tiller. A round steering wheel, able to be turned by muscle power and easier to hold in the hands, was first introduced around 1895 (Figure 1).

The brake system for very early self-powered vehicles consisted of a wooden block pressed against one of the wheels using a hand-operated lever, a technology adapted from horse carriages. A foot pedal to operate the band brake first appeared in Benz Velo in 1894 (Figure 2). The foot-operated pedal could exert greater force than a hand brake and allowed a driver to use both hands to hold a steering wheel. This could be why the steering wheel and the foot pedal appeared in the same period.

Early automobiles were not equipped with any gauges. Oil-pump gauges were the first instruments installed inside vehicles, allowing drivers to confirm the oil flow and to inject additional oil when necessary. Water-pressure gauges were also introduced around 1900. Durability was the biggest issue in the early stage of automobiles. Therefore, general monitoring of the condition of unreliable vehicles by the driver was critical and consumed considerable attention.

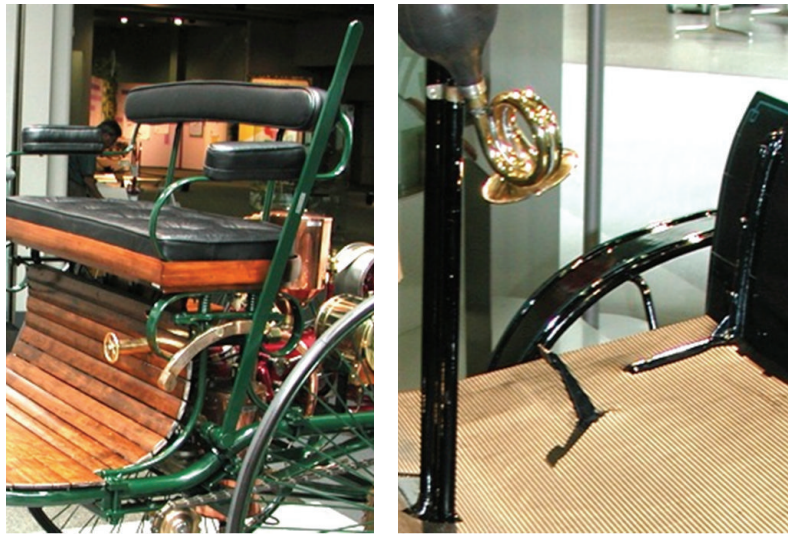
The speedometer was introduced after 1900. It was mounted outside of the bulkhead separating the engine and cab, where its cable easily fits. The speedometer was introduced to highlight the vehicle's high-speed capability. In the USA, the state of Connecticut imposed a speed limit of 8 mph within the city and 12 mph outside of the city in 1901, thus encouraging speedometer installation [2].

The manufacturer Panhard et Levassor first placed a radiator in the front end of the vehicle for effective cooling. A thermometer was installed on top of the radiator in the early 1910s, allowing the driver to read the temperature from the driver's seat. Making sure the instrument was visible to the driver and was easy to install were important design considerations. In many cases, the hood ornament on contemporary vehicles is a remnant of these instruments.

After around 1910, instruments such as tachometers and clocks were installed inside automobiles. These were directly fixed on the surface of the bulkhead, and visibility to the driver was poor (Figure 3(a)). In the late 1910s, instrument panels (or dashboards) were installed separately from the bulkheads (Figure 3(b)). The instrument panel configurations were inconsistent. Some manufacturers concentrated the gauges in the central area of the panel and others distributed them across the panel.

An indication of the importance of the industry was the growth of organizations to support it. In 1901, the later German Verband der Automobilindustrie (VDA) association of automotive industry was founded as Verein Deutscher Motorfahrzeug-Industrieller (VDMI). VDMI was established to promote road transport, defend against "burdensome measures by the authorities" (taxation, liability obligations), support customs protection, and monitor motor shows. In 1923, the VDMI was renamed the Reichsverband der Automobilindustrie (RDA). The present name Verband der Automobilindustrie (VDA) was given to this umbrella organization of the German automotive industry in 1946 (http://www.vda.de/en/verband/historie.html).

To exchange engineering ideas to facilitate the growth of the automotive industry, the Society of Automotive Engineers (SAE) was established in 1905 in the USA. The first SAE meeting was held in 1906, and since then the Transactions of the Society have been published. In the USA, standardization work began in 1910 with the first issue of the *SAE Handbook*



(a) (b)

Figure 2: Hand brake lever (Benz Patent Motor Vehicle 1886 (a)) and foot brake pedal (Benz Velo 1893 (b)) (the author's (MA) photo collection).

(a) (b) (c)

Figure 3: Meters on bulkhead (Alpha Romeo 24PH 1910 (a)), meters in instrument panel (Dodge Brothers Touring 1915 (b)), and meter cluster (Buick Series 50 1932 (c)) (the author's (MA) photo collection).

of Standards and Recommended Practices. The number of members reached more than 4,300 at the end of the 1910s [3].

In summary, the first human factors development was designing controls for the primary driving task, such as the steering wheel and the brake pedal, which allowed for operation of a heavy self-powered vehicle using only muscle power. The second development was introducing gauges to inform the driver about the mechanical condition of the vehicle and then driving condition (speedometer). In addition, industry associations established in this early stage, such as VDA and SAE, played important roles in the development and dissemination of information related to automotive technology.

2.2. The Dawn of Automotive Human Factors Design (1920–1939). During these two decades, the basic controls and displays of the motor vehicle continued to evolve. An ignition-timing lever had accompanied the steering wheel from early on. Horn buttons began to be installed in the center of the steering wheel in the late 1920s.

With regard to information presentation, gauge clusters first appeared in 1920s, often on a separate panel. Grouping gauges allowed drivers to read them at a glance. However, most gauge clusters were placed in the center of the instrument panel.

Before the 1920s, switches or knobs typically did not include labels to indicate their function. Drivers had to learn and memorize the function of each. Labels first appeared on controls and on the surface of instrument panels in the 1920s.

In the 1930s, speedometers and other instruments began to be installed directly in front of drivers to improve their visibility (Figure 3(c)), a practice that became common in the 1940s. American and many European luxury automobiles in this period were equipped with a shift lever on the steering column.

In early vehicles, one signaled the intention to turn using a *winker*, a mechanically operated arm or flag that extended

Figure 4: Turn indicator (BMW 335 1939, courtesy of H. Bubb).

from the side of the vehicle, first appearing in the 1910s. The exterior signal became a mechanical semaphore in the 1930s (Figure 4) and, finally, an electric light in the 1950s in Germany. A turn-signal switch or turn-signal lever was also being installed in the steering column by the late 1930s (Figure 5).

The seat-sliding mechanism, which adjusts the driving position, appeared in the 1920s. It allowed drivers with different body sizes to find a reasonable distance between the pedals and the seat.

Until the 1930s, the focus of automotive technology was on meeting basic functional requirements, primarily mechanical, to provide a durable vehicle. The shift at that time was toward designing vehicles that could go faster, with the 1934 Chrysler Airflow and its emphasis on aerodynamics as an example. Consequently, cabs shrunk and the car body became more rounded. This, in turn led to efforts to design the cab layout to fit the human body size and provide increased seating comfort while maintaining outward visibility. In an early book on automotive engineering written by Wunibald Kamm, an automobile engineer and an aerodynamicist famous for his Kamm-tail theory, provided an example of desired cabin dimensions (Figure 6) [4].

Thus, basic human factors design features, such as easy-to-operate steering equipment and switches, visible gauges, and a reasonable driving position, were introduced during the 1930s and 1940s. Note that, throughout that period, design decisions to accommodate human operators and passengers were based largely on heuristics from engineers' experience. Also numerous features were designed and implemented to ease the driving task, such as synchronized gears and improved windshield wipers, as well as switchable low and high beams. For additional information on these and prior developments, see [1, 2, 5].

The number of traffic crashes increased after World War I as the production of automobiles increased. In 1920, German psychologist Narziss Ach outlined the importance of psychology and technology in preventing crashes from the perspective of a scientific discipline that he called *psychotechnik*, which is closely related to human factors [6]. At the end of the 1930s, Forbes pointed out that understanding the limitations of driver capabilities such as visual characteristics and reaction time, "human factors" in traffic crashes, was necessary [7]. Both engineers and psychologists were aware of the importance of the human element in vehicle design and traffic safety in this period.

3. Human Factors Activities after World War II until 1989: The Era of Occupant Accommodation and Safety

3.1. Establishment of Human Factors as a Field of Endeavor (1940 to 1949). Although one can identify the roots of human factors being in early work in industrial engineering, such as that of Taylor and Gilbreth, activities at Bell Labs on communication quality, and other examples, human factors as a profession did not take off until WWII [8]. Human factors research was introduced during World War II to adapt military technologies to human operators to make systems more effective and reliable [9–11]. This research field was then expanded to the commercial aviation and automotive industries after World War II.

There was not an immediate transfer of human factors ideas from military to civilian activities. In part, this was because the initial transfer was from military organizations to defense contractors, which took several years, and Europe and Japan were recovering from World War II.

However, this period was not without some progress. Passive-safety technology was introduced at the end of the 1940s. The instrument panel was covered with sponge rubber in American automobiles, by Tucker in 1948 and Chrysler in 1949.

Also, there was considerable growth in the organizations interested in automotive research, some shortly after World War II, others later. The earliest one was British Motor Industry Research Association (MIRA) (UK), founded in 1946.

The following sections briefly describe automotive human factors studies and their output (mainly standards) and outcomes (products) from 1950 to 1989 by decade. Table 1 summarizes the major developments for each decade.

3.2. Human Factors Research Activities in 1950s: First Decade of Human Factors Research. A survey of the literature on human engineering in the 1950s, conducted by the U.S. Army Human Engineering Laboratory [12], indicated that studies at that time focused on driving visibility (including glare), cab layout based on anthropometric data, and the design of controls.

With regard to anthropometry, in 1955, for the first time, the SAE published data that included 5th- and 95th-percentile values for use in cab layout (Figure 7) [13]. During this decade, research was also conducted on human-body

Table 1: Overview of history of human factors researches, their outputs and outcomes.

			Empirical human factors design					WWII						
			1886–1899	1900–1909	1910–1919	1920–1929	1930–1939	1940–1949	1950–1959	1960–1969	1970–1979	1980–1989	1990–1999	2000–2009
Primary driving task	Controls	Human factors research and output	Empirical: control by human muscle power			Empirical: access controls while holding steering	Empirical: access controls while holding steering		Symbols to indicate function of controls		Anthropometrical data for hand reach (SAE J287, 1976), Standardized direction of movement of control (SAE J1139, 1977)			
		Outcome	Steering wheel, Foot pedal,			Horn button and timing lever around steering wheel Labels indicate its function	Shift lever, turn signal lever around the steering column		Comprehension of function for people with different languages		Designing location of controls Common design of control direction	Steering wheel switch	Integrated joystick (Toyota, 1998)	i-Drive with controller nob in the center console (BMW, 2001), integrated center control (Nissan 2001)
	Displays	Human factors research and output		Empirical: obtain information about vehicle condition	Empirical: visible information	Empirical: decrease amount of eye movements to check meters and gauges	Empirical: smaller eye shift to access the meter cluster		Empirical: smaller eye shift to access the meter cluster Avoid influence of sunlight		Symbols for Motor Vehicle Control, indicators, and tell tales (SAE J1048, 1974, ISO2575)	Investigation of advantage of HUD for vehicle display (1970s)	Measurement of visual accommodation (Toyota 1998)	
		Outcome		Installing gauges and speedometer	Instrument panel with meters and gauges	Clustered meters in instrument panel	Meter cluster in front of driver		Meter cluster in high position with sunshade		Commonly used symbols	Introduction of HUD for vehicle display (GM, Nissan 1988)	Introduction of center on-dash meter (Toyota)	
	Visibility to road scene	Human factors research and output		Empirical: perceive approaching vehicles from behind	Empirical: road scene visibility in rain condition					Motor vehicle drivers' eye locations (SAE J941, 1965), Eyellipse (SAE Paper 680105, 1968) Passenger car rear vision (SAE J834, 1967)	Regulation for rear view mirrors (Directive 71/127/EEC, 1971), Field of view from automotive vehicles (SAE SP-381, 1973)	Backing sensor	Investigating visibility using digital human model Rear view monitor	Night Vision System
		Outcome		Rear view mirror	Windshield screen wiper					Define range of drivers' eye positions Examine direct visibility	Specifying visible area in rear view mirrors Investigating location of traffic signals, traffic signs, pedestrians in the driver's view		Time and cost effective design of visibility using CAD	

Table 1: Continued.

			Empirical human factors design					WWII						
			1886–1899	1900–1909	1910–1919	1920–1929	1930–1939	1940–1949	1950–1959	1960–1969	1970–1979	1980–1989	1990–1999	2000–2009
Driver Workspace	Seating and packaging	Human factors research and output				Empirical: adapt to women drivers	Design drawing		Anthropometrical data for human body (SAE SP142A, 1955), SAE Manikin Subcommittee (1959)	Defining and measuring H-point (SAE J826, 1962), 2DM, 3DM	Chrysler's Digital Human Model CYBERMAN (1974), Measurement of pressure distribution of seat	SAMMIE, CAD with digital human model, is in the market	Commercial digital human model, Ramisis, Jack Body movement analysis using motion capture system	Combining digital human model with CATIA and ALIAS CAD, estimating muscle load using DHM
		Outcome				Seat adjuster	Cabin space design			Cabin space and seat layout design Precise design of seating configuration based on H-point,	Designing seat back angle		Time and cost effective design of packaging	Evaluation of ingress/egress motion
	Vibration and comfort	Human factors research and output		Frederick Lanchester (UK) proposed the cabin movement is to be the same as that of human body while walking				Seat cushion and comfort (SAE 1940')	Motor Vehicle Seating Manual (SAE J782, 1954)		Relationship between mechanical vibration and discomfort (ISO 2631, 1974)	Analysis of resonance frequency of body parts	Evaluation of vibration discomfort in multiaxis environment (ISO 2631-1, 1997)	Temporal factor in vibration discomfort
		Outcome		Peak frequency of cabin vibration was about 2.0 Hz							Establish evaluation method for vibratory comfort	Designing cushion of seat	Evaluation to integrate vibration in multiaxis	
	Climate	Human factors research and output			Empirical: comfort in winter time							Thermal manikin	Equivalent temperature (SAE J2234, 1993)	Ergonomics of thermal environment of vehicle (ISOI4505 series)
		Outcome			Cabin heater							Evaluation of vehicle climate	Evaluating thermal comfort using Equivalent Homogeneous Temperature	Evaluation of cabin thermal comfort, combining thermal manikin, calculation of EHT, and subjective evaluation

Table 1: Continued.

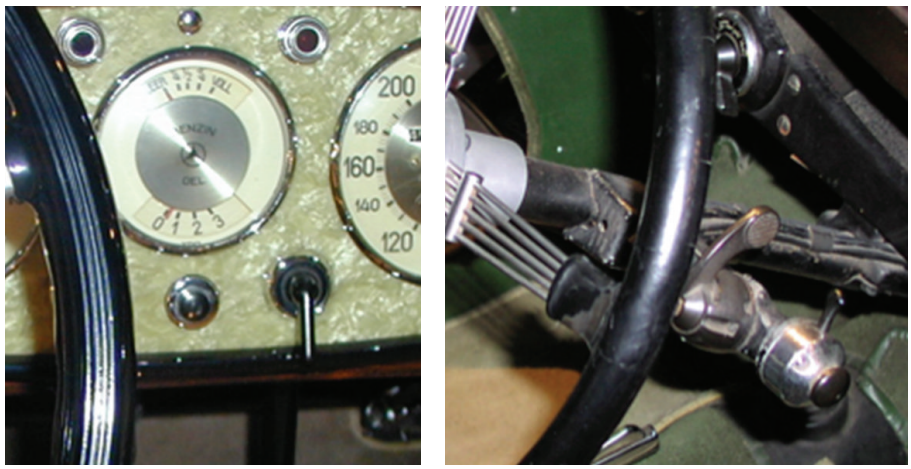
			Empirical human factors design					WWII						
			1886–1899	1900–1909	1910–1919	1920–1929	1930–1939	1940–1949	1950–1959	1960–1969	1970–1979	1980–1989	1990–1999	2000–2009
Driver's condition	Driver's Fatigue	Human factors research and output								Physiological measure for fatigue (HR, GSR, BP) CFF study Recommendation of having rest Evaluation of vehicle vibration		HRV as a measure of fatigue		
		Outcome												
	Impairment	Human factors research and output									Physiological measure for drowsiness, EEG, EOG, GSR	Partial eye closure as a measure of drowsiness (Dingus, 1986)	Percentage of eye closure as measure of drowsiness (PERCLOS)	
		Outcome										Algorism to detect drowsiness (NHTSA DOTHS808247, 1994)	Drowsiness detection system	
Crash injury		Human factors research and output						Instrument panel covered by sponge rubber (Tucker 1948, Chrysler 1949)	Investigation of body damage by accident Crash test using high speed camera Crash dummy (GM, Ford) Seat belt (Nash, 1949)	Crash dummy, FMVSS208 frontal crash test in 30 mph (1966)	Crash dummy, Hybrid II (1974), Hybrid III (1978) Injury index AIS-1971, AIS-1976	Dummy, Euro-SID-1 for side impact (1989)	Dummy for side impact, Bio-SID, more sensors and more biofidelity, (1990) and SID-II (1994)	
		Outcome							Nondeformable passenger cell (Daimler-Benz 1952) 3-point seatbelt (Volvo, 1959) Head restraint (AM, 1959)	Collapsible steering column (GM, 1967) Mandatory belt use in front seat (1967, USA; 1969, Japan)	Standardized assessment method	Airbag	Side impact bar, Side airbag	
Interaction with driver information system		Human factors research and output								There was tolerable visual sampling duration while driving (Senders, 1967)	Measurement of eye movement on in-car displays (Mourant, 1978)	Visual sampling model and glance time study (Wierwille)	Visual behavior and driving performance as a measure of distraction (Zwahlen, 1986), mental workload measures	Workload measurement for distraction: occlusion method (ISO16673, 2007) and LCT (ISO26002, 2011)
		Outcome									Single glance time was 0.5–1.5 seconds. Several glances for radio task	Assessment of IVIS using glance time	Discussion of map display JAMA guideline ver. 1.0 (1990), ver. 2.0 (1999) HARDIE guideline (1995)	Guidelines (JAMA ver. 3.0 (2004), AAM etc.) for information device

Table 1: Continued.

		Empirical human factors design					WWII					
		1886–1899	1900–1909	1910–1919	1920–1929	1930–1939	1940–1949	1950–1959	1960–1969	1970–1979	1980–1989	1990–1999	2000–2009
Interaction with advanced driver-assistance system	Human factors research and output												Overreliance, overtrust, and situation awareness with ADAS Analysis of driving behavior
	Outcome							Conventional cruise control			Antilock Braking System (ABS)	Electronic stability control (ESC), vehicle stability control (VSC) Adaptive cruise control (ACC) in the market, night vision	Lane-keep assist Full-range ACC Collision mitigation braking system
External communication access	Human factors research and output								Visual demand while driving (Senders, 1967)			Accident statistics analysis for risk of mobile phone use while driving	Naturalistic driving study
	Outcome									Cellular automobile phone service (ARP Finland, 1971; NTT, Japan, 1979)	Analog cellular service (US 1984)	Prohibition of hand held use of cellular phone (Swiss, 1996; Japan, 1999)	Regulations for use of cellular phone (USA, 2001 (NY), Germany, 2001; France, 2003; UK, 2003)
Driving behavior	Human factors research and output								Driver vehicle control model Development of early DS (GM)	Visual behavior while driving using eye tracker	Researches on UFOV	Visual attention measured by peripheral detection task	Naturalistic Driving study Driving behavior study using DS
Related technologies and vehicles' environment		Very rough road	Increased speed		Radio tuner was installed		Highway mobile telephone (USA, 1946)		Development of highway		RDS-TMC (EU)	Telematics service (US OnStar 1995, Germany TeleAid 1997 BMW Assist 1999, Japan MONET 1997, Carwings 1998)	Smart phones

Table 1: Continued.

	Empirical human factors design					WWII						
	1886–1899	1900–1909	1910–1919	1920–1929	1930–1939	1940–1949	1950–1959	1960–1969	1970–1979	1980–1989	1990–1999	2000–2009
Organization and academic society		VDMI (currently VDA, Germany, 1901), SAE (USA, 1905)		SIA (France, 1927)		JSAE (Japan, 1947), FISTA (1948)	HEFS (USA, 1956), IEA (1959)	JSAE automotive ergonomics study group (Japan, 1962)		HFES Europe Chapter (1983)		
Public institutions				VTI (Sweden, 1923)	TRL (UK, 1933)	MIRA (UK, 1946), TNO human factors (The Netherland 1949)	TTI (USA, 1950), BASt (Germany, 1951)	ONSER (road safety org France, 1961), UMTRI (USA, 1965), JARI (Japan, 1969), TNO Traffic Behavior Department (The Netherland 1969)	NHTSA (USA, 1970), HUSAT (UK, 1970), IRT (France 1972)	INRETS/LESCO (combining ONSER and IRT, currently INFSTTAR/LESCOT) (France 1986)		
Conference meetings		SAE conference (USA, 1906)		TRB (USA, 1920)		FISITA congress (1947)	JSAE conference (Japan, 1951), HFES meeting (1957)	IEA congress (1961), Stapp (USA, 1962)	ESV conference (1971)	Vision in Vehicle (1985)	AVEC (1992), Driving Simulator Conference (1994), ITS World Congress (1994)	Driver Assessment Conference (USA, 2001), International Conference on Driver Distraction and Inattention (EU, 2009), AutomotiveUI (2009), HUMANIST (EU, 2008)
Social background		Speed violation penalty		Increase of number of vehicles (USA)			Increase of number of vehicles (Europe)	Media promotion for safety (Chevrolet, Corvair USA)	Media promotion for safety (Ford Pinto, USA)	Media promotion for safety (Jeep CJ05, Suzuki Samurai, Audi 5000, USA)	Media promotion for safety (GM CK pickup, USA)	Media promotion for safety (Ford Ram, Crown Victorias, Explorer, USA)



(a) (b)

Figure 5: Turn signal lever in instrument pane (Mercedes-Benz 500K 1935) and that in steering column (Morris Eight Series I 1937) (the author's (MA) photo collection).

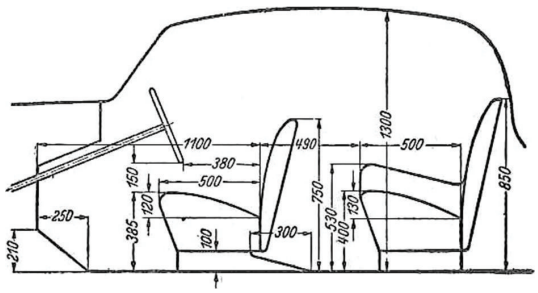


Figure 6: Cabin dimensions shown in Kamm's book "*Das Kraftfahrzeug*" (1936).

injuries caused by vehicle crashes [14]. Experimental technologies for crash tests (e.g., dummies, accelerometers, and high-speed cameras) were developed [15].

Following up on some advances in passive safety earlier in the 1940s, Nash Motors installed the first seatbelt in 1949. Other American manufacturers introduced seatbelts in the 1950s. In 1952, Barényi, an engineer at Daimler Benz, invented the nondeformable passenger cell and in later years, the crumple zone and collapsible steering column.

Some European vehicle manufacturers in this period introduced symbols to indicate the functions of controls. The position of the gauge cluster was raised to be closer to the normal line of sight and, therefore, was easier to read.

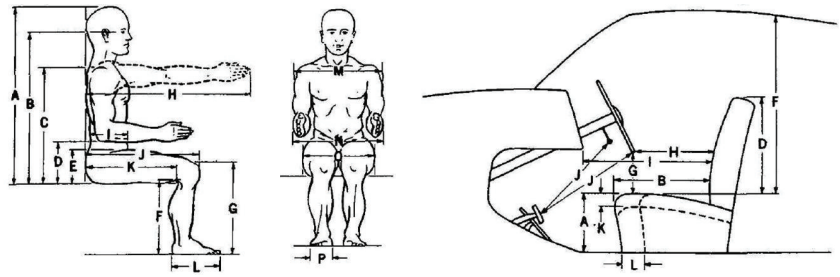
Subsequent to MIRA's founding in the UK in 1946 was the founding of Texas Transportation Institute (TTI) (US, 1950), German Federal Highway Research Institute (BASt) (Germany, 1951). Also established around this time were organizations specifically focusing on safety and human factors—TNO Human Factors (The Netherlands, 1949), ONSER (road safety organization, currently INFSTTAR, France, 1961) and the automotive ergonomics study group in JSAE (Japan, 1962).

A variety of automotive human factors research efforts began during this period. Methods from psychology, medicine, and anthropology were introduced. An important method involved using statistical distributions of anthropometric dimensions to establish vehicle design standards for those dimensions. This method directly linked human factors research to production of vehicles geometrically adapted to human characteristics, a method that was developed further in the next decade.

3.3. Human Factors Research Activity in 1960s: The Decade of Anthropometry. In the 1950s, automobile manufacturers recognized that anthropometric data could be the basis for laying out the cab to ensure that the driver (1) could see the road, traffic signals, and other vehicles outside of the cab, (2) could see controls and displays inside the cab, and (3) would be able to reach controls. In 1959, the SAE Manikin Subcommittee began developing an easy-to-use tool for ergonomic design based on anthropometric data. The SAE two-dimensional manikin (2DM) and three-dimensional manikin (3DM) were codified in SAE J826, which was published in 1962 [16]. The hip-point (H-point), which was the origin on the human body for automotive cab design, was defined in this standard together with specific measurement procedures. The 2DM was used to design the side view of the vehicle, and the 3DM was used to design cab mockups.

Based on the anthropometric research, the driver's eye position was defined in SAE J941, and the concept of the eyellipse, which specified the range of the driver's eye position, was developed [17–19]. What drivers of widely varying body sizes would be able to see could be examined using the eyellipse. Standards for front-view and rear-view visibility were also published (SAE J834, 1967) [20].

At that time, automobiles were commonly used in the USA and driven by a wide range of people. Therefore, the US car manufacturers were motivated to collect anthropometric data for cab design to accommodate that range



(a) (b) (c)

Figure 7: Human body measurements and vehicle dimensions shown in SAE SP142 (1955).

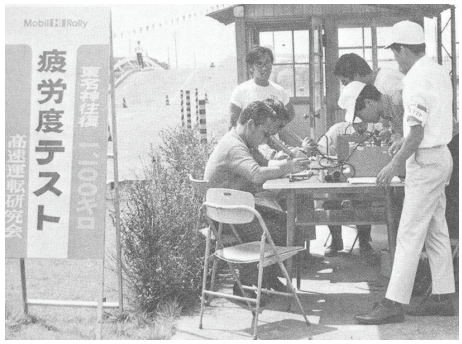


Figure 8: Field experiment of Critical Fusion of Flicker (CFF) measurement for highway drive in Japan (Brochure of IPRI, AIST, 1969).

Figure 9: Helmet for occlusion device (courtesy of J. W. Senders).

of drivers [21]. This data was also helpful to car manufacturers outside the USA who were developing cars for export to the USA and served to further improve various SAE standards that had been developed or were in development.

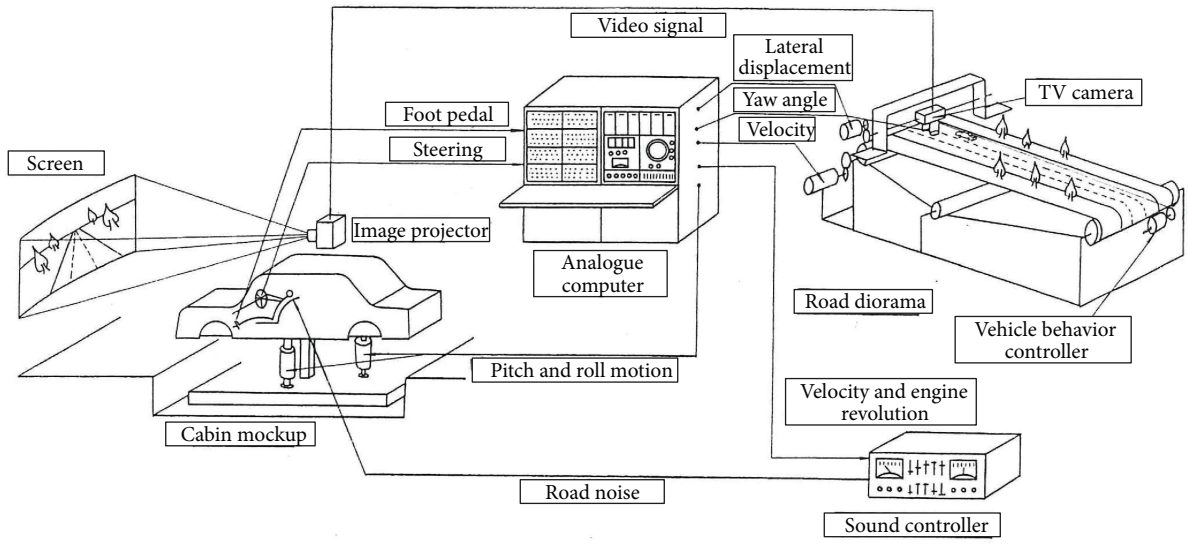
Frontal-crash test procedures to protect occupants were introduced in FMVSS 208 [22]. In 1959, Volvo was the first manufacturer to provide three-point seatbelts. In the same year, American Motors also equipped their automobiles with head restraints to avoid neck injury in rear-end collisions. In 1967, General Motors conducted pioneering work on collapsible steering columns designed to reduce chest impact injuries [5].

The construction of special-purpose, high-speed roads began with the first autobahn in Germany in the 1930s, followed by construction of interstates (USA), autoroutes (France), motorways (UK), and autostrada (Italy) beginning in the 1950s, and followed by significant highway construction in Japan in the 1960s. Because trips on such roads tended to be long, driver fatigue became a concern. There were many studies done in Japan, mainly by researchers with medical backgrounds, to evaluate driver fatigue using such physiological variables as heart rate, GSR (galvanic skin response), blood pressure [23], and CFF (critical frequency fusion) (Figure 8).

With the development of control theory, studies were conducted to apply this theory to steering maneuvers [24–28]. Studies to measure mental workload, introducing methods from physiology and the cognitive sciences, began in the 1960s. Brown and Poulton assessed drivers' spare mental capacity using auditory subsidiary tasks requiring the driver to identify a digit that differed from the previous one [29]. One pioneering study on driving behavior was Sender's 1967 study to measure visual demand while driving, using an occlusion device with a moving frosted plastic visor on the helmet (Figure 9) [30].

During the 1960s, driving simulators were developed to study vehicle dynamics and to analyze driving behavior. It is not certain when the first simulator was developed, but there were driving simulators in the 1950s. General Motors developed a driving simulator using a gimbal structure to give pitch and roll motion to the driver [31]. The driving simulator developed in 1976 by the Mechanical Engineering Laboratory of AIST (Japan) had a moving cab, and the driving scene was obtained through a movie camera running a miniature diorama of a road in town and in a rural area (Figure 10) [32]. Driving simulators were also developed in US universities. Interestingly, it was not until about 17 years later, with the advent of the Daimler-Benz simulator, that driving simulators received broad attention [33].

In the USA, a major factor in the movement to improve crash safety was the investigative news media. The first vehicle to attract attention was the 1961–1963 Chevrolet Corvair, which in a sharp turn, had a tendency to spin and/or rollover. The Corvair was an unusual rear-engine vehicle, and there



(a)

(b)

Figure 10: Driving Simulator of Mechanical Engineering Laboratory of AIST (1968) (Technical Report of MEL, no. 89, 1976).

was considerable discussion of its suspension system in a book by Ralph Nader, a consumer advocate [34]. The book's title, *Unsafe at Any Speed,* captured the way some felt about Corvairs. As a result, there were congressional hearings about vehicle safety (that led to a black eye for General Motors), eventual withdrawal of the Corvair from production, and a significant increase in interest in vehicle safety.

The interest in safety led to the establishment of the Highway Safety Research Institute at the University of Michigan, now the University of Michigan Transportation Research Institute (UMTRI), in 1965 and the National Highway Traffic Safety Administration (NHTSA) in the U.S. Department of Transportation in 1970. TNO in The Netherlands started a Traffic Behavior Department in 1969, which focused on traffic safety. In the same year, Japan Automobile Research Institute (JARI) was founded. They joined a worldwide collection of organizations (see Table 1).

The growth in the worldwide production of automobiles led to increased interest in designing vehicle cabins suitable for a wide range of people. As the number of traffic accidents rapidly increased with increased production, safety became a major concern for society. Automotive safety technology had evolved since the last decade, but it was facilitated by news media in this decade. Human factors research led first

to advances in passive safety and later to advances in active safety. Research on measurement of fatigue, mental workload, and driving-task demand developed in this decade. A shift in human factors research began from a focus on physical characteristics to cognitive characteristics.

3.4. Human Factors Research in the 1970s: Establishing Crash-Safety Assessment and Occupant Comfort. The impact of the US news media in bringing attention to crash safety continued in the early 1970s, focusing on the Ford Pinto. When struck from the rear under certain circumstances, Pintos would dramatically catch fire [35–37], videos of which are still available (http://www.youtube.com/watch?v=rcNeorjXMrE, http://www.youtube.com/watch?v=lgOxWPGsJNY). A critical document in the case was a cost-benefit analysis done by Ford, which compared the cost of making changes to the vehicle to prevent or reduce fires with the cost of injuries and lives lost, an idea that has been the source of numerous ethics discussions over time. However one feels about the Pinto, the case generated an intense focus on vehicle safety, in particular with regard to fires and safety in crashes, especially rear-end crashes. As with the Corvair, the Pinto's poor publicity led to a sharp decline in sales and eventual withdrawal of the Pinto from production. The Pinto case served as the stimulus for further research in the USA.

To help prevent rear-end crashes, Irving and Rutley investigated staged signaling concepts for different braking levels, conveying more information to following vehicles, concepts that led to improved braking over those in use [38]. Also the number and position of brake lights varied, leading to the idea of center, high-mounted stoplights. The effectiveness of the high-mounted stoplight was studied in the 1980s [39, 40]. During this decade, there were also studies of nighttime visibility distance of different headlight beam patterns and technologies (conventional tungsten, sealed beam, and halogen), as well as their effects on glare [41].

Improved understanding of what happened in crashes was also a research focus. Crash dummies were developed by several different organizations. They were integrated into Hybrid I in 1971 and Hybrid II in 1974. Sensors in Hybrid II were located in the head, chest, and femur. To make the dummy more realistic, Hybrid III was developed in 1976 [42]. Ten sensors were located in the head, neck, upper body, femur, knee, and leg, where injury might occur in the event of a crash. The severity of injury of each part of the body could be assessed based on the acceleration of each location. Head Injury Criteria (HIC) were defined by NHTSA in 1971 to assess the severity of head injury using the dummy. The Abbreviated Injury Scales (AIS-1971 and AIS-1976) for determining the level of injury produced by actual accidents were also established during this decade. The assessment method was standardized during this period [43].

However, crash safety was not the only topic of interest during the 1970s. Based on anthropometric research, an SAE standard for hand reach was published in 1976 (SAE J287) [44, 45]. To reduce driver confusion when operating controls, the direction of the movement of controls was standardized in SAE J1139 in 1977 [46].

Symbols to indicate control functions were introduced in the 1950s, mainly for European cars, to avoid the need to produce a different instrument panel for each language region in which a vehicle was sold. These symbols did not require reading written words and were intended to be intuitive. However, when different symbols were used to indicate the same function, drivers could become confused. To avoid such confusion, standard SAE J1048 was established in 1974 [47].

Studies on vehicle vibration and comfort have been conducted since the 1940s. Vibration and shock may cause low back pain and performance changes [48]. Vibration of the vehicle's cab occurs along all three axes, both linearly and rotationally. The most important is vertical movement transferred though the vehicle suspension and car seat. A method to estimate the perception of discomfort was standardized in ISO 2631 in 1974 [49].

In addition to specific research topics, research tools were developed and improved in this decade. Eye trackers, devices used to measure eye-gaze location, became available for vehicle and simulator use in the 1970s. For example, Mourant, Rockwell, and others measured glance time to the mirrors, radio, and the road while driving for novice and experienced drivers [50].

The driving simulator became a tool in human factors research. Volkswagen developed a driving simulator with a three-axis gimbal. A CRT display was used to present a road scene that involved a computer-generated line drawing. Various sounds were also presented. This driving simulator was used to investigate the driver's evasive behavior [51]. A driving simulator using a linear rail was developed at Virginia Tech in 1975 [52].

This most noteworthy result of this decade was the translation of human factors research into practice. Various standards were prepared to design controls and to evaluate seating comfort. Crash dummies were established and utilized by the New Car Assessment Program (NCAP), which began in 1979 in the USA.

3.5. Human Factors Research in the 1980s: Computer-Aided Design for Automobiles, Cab Comfort, Rollovers, and Assessment Methods. As with every recent decade in the USA, the 1980s had a particular vehicle that received attention for issues related to crashworthiness. That vehicle was the Jeep CJ-5, whose rollover propensity was the subject of a broadcast by *60 Minutes*, the most-watched investigative news program on US television. The critical episode, broadcast on December 21, 1980, showed Jeep CJ-5s rolling over when making sharp turns. What many fail to recall is that there was supporting statistical data showing that the CJ-5 was much more likely to roll over than other similar vehicles [53, 54]. For an interesting summary, see [55]. The CJ-5 problems served to spark human factors research on vehicle handling.

Another vehicle that received attention in that decade was the Suzuki Samurai, a short wheelbase, four-wheel drive utility vehicle with a propensity to roll over. Suzuki had a very bitter legal battle with the Consumer's Union, which publishes the most popular consumer magazine in the USA,

Consumer Reports. Unusually, the vehicle was rated as "not acceptable." Sales dropped from 77,500 vehicles in one year to 1,400 the next year. Suzuki sued the Consumers Union but lost, and the production of the Samurai ceased. The Suzuki case emboldened safety advocates who had been sometimes reluctant to challenge the auto companies with "deep pockets" to fund protracted legal actions.

Allegations of unintended acceleration of the Audi 5000 were publicized on *60 Minutes* on November 23, 1986 [56]. Again, given the bad publicity, sales of the Audi 5000 plummeted from 74,000 vehicles in 1984 to 12,000 in 1991. Ironically, the final verdict from the U.S. Department of Transportation was that, while there were design aspects that could startle drivers or contribute to a higher incidence of pedal misapplication, there was nothing requiring a defect notification [57]. The important point here is that this is probably the first time that questions raised by the news media about vehicle safety were not supported by further investigations.

Interestingly, in recent years, there again have been questions raised concerning unintended acceleration; this time was for Toyota vehicles. *Dateline NBC* was the program involved, but in some ways the Toyota case is strikingly similar to that of the Audi 5000. There were allegations of trapped floor mats and concerns about failure of the electronic control systems, a claim that was debunked by NASA [58]. Again, Toyota sales suffered as a consequence, but no vehicles were withdrawn from the market.

In 1980, Brown stated that the improvement in the crash statistics "has undoubtedly resulted from technological advances in the design of steering, braking, tires and suspension systems, affording the driver better control of his vehicle" [59, pages 3–14]. He also emphasized the importance of optimizing information presentation in the vehicle and introducing objective evaluation and quantification instead of pure subjective assessment.

New tools for designing cab dimensions and visibility were developed in the previous decade. Chrysler developed CYBERMAN, a digital human model (manikin) in 1974. However, it was simple and its usefulness was limited. The System for Aiding Man-Machine Interaction Evaluation (SAMMIE) was developed in the UK for a consulting service for ergonomic design by SAMMIE CAD, Ltd., in the 1970s. The three-dimensional, digital human model consisted of 21 links and 17 joints. The cab dimensions and layout of controls in the cab could be evaluated by specifying the joint angles of the three-dimensional human model based upon anthropometric data of representative drivers. Various digital human models were developed during this period. Linked with computer-aided design (CAD), digital human models worked effectively. SAMMIE worked with SAMMIE CAD system, but interchangeability with other systems was limited. Jack (USA), RAMSIS (Germany), and other digital human models were developed during this period. RAMSIS could link with the CATIA CAD system, which was and still is the most commonly used CAD system in the automotive industry. Compared with the traditional anthropometric data and hard manikins, digital human models can lead to shorter development times of vehicle cabs, reduce development cost, and lead to cabs that accommodate a larger fraction of the population [60, 61].

Head-up displays (HUDs) were initially developed for aviation and superimpose information of aircraft air speed, altitude, and angle of attack onto the forward view. As eye transition and accommodation times were reduced, the user could spend more time looking at the forward scene. In motor vehicles, HUDs have been used to show vehicle speed, warnings, turn signals, and more recently, navigation information. The first studies with HUD prototypes were conducted by Rutley [62], who showed that HUDs can have benefits without the negative distracting effects reported in aviation applications [63]. HUDs were introduced in the market at the end of the 1980s (General Motors 1988, Nissan 1988). As the initial application was to present speed, which was not as time-critical as the flight data shown in aircraft, the customer demand for automotive HUDs when introduced was not great.

Also occurring at this time was considerable research to assess human thermal comfort [64], research that has its origins in Willis Carrier's development of the psychrometric chart [65]. The factors contributing to human thermal comfort, air temperature, radiant temperature, air velocity, humidity, metabolic rate, and the distribution and insulating value of clothing were not all easy to measure in a real vehicle cab. To evaluate space-suit thermal comfort, in 1966, NASA developed a thermal manikin that had a three-dimensional human body and simulated the heat transfer between the human body and the thermal environment. By the end of the 1970s, thermal manikins were used to estimate thermal comfort in vehicle cabs [66].

Drowsiness while driving increases crash risk. A driver's drowsiness, arousal level, and fatigue can be measured using such physiological variables as EEG (electroencephalogram), heart rate, respiration rate, and GSR (galvanic skin response) [67]. As was shown in early studies, physiological measures could be reliably measured in experimental conditions and provided useful information. However, it was difficult to convert the research into practice and develop a commercial drowsiness-detection system, primarily because wired sensors were needed. Thus, in the 1980s there was a shift towards noncontact image sensors (video cameras) that looked for slow eyelid closure to detect drowsiness [68]. Studies were conducted to obtain quantitative measures based on video images, and in the next decade PERCLOS (percentage of eyelid closure time) was established as the index of drowsiness [69]. In 2008, Toyota introduced a crash-mitigation system with eye monitor that detected eyelid closure and warned the driver.

Workload-measurement methods were established during the 1970s [70]. These methods used subjective measures (the Cooper-Harper scale, SWAT-the Subjective Workload Assessment Technique, and NASA TLX-the Task Loading Index), primary task performance measures, secondary task measures (from the task loading and subsidiary task methods), and physiological measures (EEG, pupillary response, eye movement, and heart-rate variability). They were used to measure mental workload while driving. Miura collected detection-reaction times to the illumination of small bulbs

located around the front window, as the subsidiary task, to measure the useful field of view [71]. Results indicated that the useful field of view became smaller, and the reaction time of a detection task became longer as task demands increased (e.g., driving in crowded traffic).

With increasing computer power, large driving simulators were developed in the 1980s. In the 1970s, VTI of Sweden began developing a driving simulator with a two-axis gimbal and a linear rail. It had a wide screen and was controlled by a detailed vehicle-dynamics model [72]. An example of its use, which began in 1983, was the investigation of driving on slippery roads and the effects of alcohol. The major development was the Daimler-Benz high-fidelity driving simulator with a motion system that combined the hexapod motion platform and two-dimensional linear rails. A full-size vehicle was placed in the dome on the motion platform. It was introduced in 1984 and was used to investigate active-safety systems, vehicle dynamics, and other topics [73]. During the 1980s, various driving simulators were developed in the USA, Europe, and Japan [74]. Common topics in the 1990s included studying driving behavior in risky conditions, the use of driver information systems [75–78] and the use of advanced driver-assistance systems (ADAS) [79, 80] and the effectiveness of warning systems of various types. One example was using the pedals and steering wheel to provide active feedback to facilitate drivers' performance of a recommended action [81].

The end of the 1980s saw the beginning of an era of driver information and driver-assistance systems (see the next section). One early human factors study of driver information systems involved measuring glance time and number of glances for a variety of conventional tasks and navigation tasks using a prototype computer map navigation system [82]. One study indicated that centerline deviation increased when the driver used a CRT touch screen [83].

The 1980s were the decade of the computer. Digital computers and software began to see wide use in human factors research, including digital human models for designing cabin accommodations, thermal manikins for evaluating thermal comfort in the cabin, and video systems for measuring drowsiness. Computer technology reduced design time and made handling complex data easier. The questionnaire and the secondary-task methods were established for mental-workload measurement based on resource models from psychology. These measurement methods and driving-simulator technology would become useful human factors research tools for the intelligent vehicles and connected vehicles in the following decades.

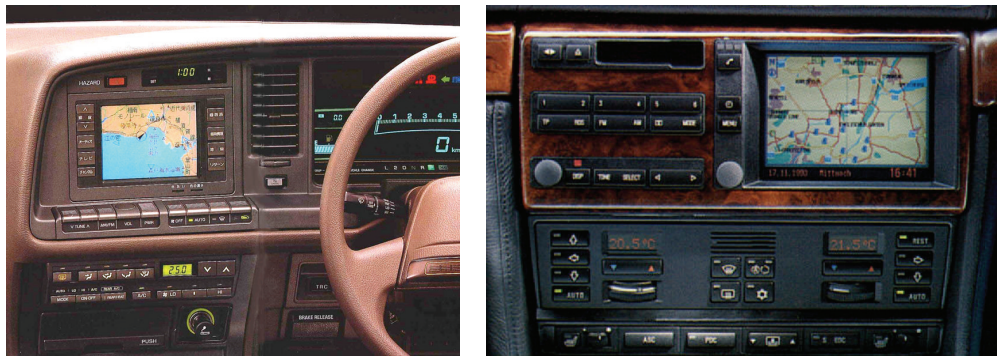
4. Human Factors Research Since 1990s: The Era of Intelligent Vehicles and Connected Vehicles

4.1. Driver Information Systems and Driver Distraction. Research on automotive human factors reached a turning point in 1990 with the introduction of Intelligent Transportation Systems (ITS), previously known as Intelligent Vehicle Highway Systems (IVHS). With the aim of enhancing vehicle mobility and safety using information and communication technologies, government projects began in the USA and Japan. The Electronic Route Guidance System (ERGS) was conducted in the late 1960s in the USA [84]. The Japanese projects included the Comprehensive Automobile Traffic Control System (CACS) (1973), Road/Automobile Communication System (RACS) (1984), Advanced Road Transportation System (ARTS) (1989), and Vehicle Information Control System (VICS) (1990) [85]. Europe's research initiative Programme for European Traffic of Highest Efficiency and Unprecedented Safety (PROMETHEUS) (1987–1995) initiated the research era of driver information and driver-assistance systems [86]. PROMETHEUS was followed by a sequence of projects (e.g., DRIVE, GIDS, EMMIS, HASTE, and AIDE) that focused on the development of integrated HMI concepts [87] and suitable evaluation methods [88].

The automotive industry also promoted ITS technology developments during this period. In 1981, Honda released Gyrocator, the first in-vehicle navigation system with a map using a transparency sheet. At about the same time, Toyota released NAVICOM, which indicated the direction of a destination using a simple arrow. Etak Navigator, the first after-market car navigation system using a digital map, was released in 1985 in the USA. The digital map was stored in cassette tapes and location was determined by a dead-reckoning system using a compass. In 1987, Toyota launched Electro Multi Vision, which was a predecessor of present-day, in-vehicle car navigation systems (Figure 11). An in-vehicle navigation system manufactured by Sumitomo Electric was installed in the Nissan Cima in 1989 [89]. The Bosch Travelpilot was delivered in the same year in Europe. In-vehicle navigation systems spread after GPS became available in 1990 (officially in 1993). The first on-board installed navigation system including a GPS unit and map material in Europe was delivered in 1994 by BMW using a color-TFT display and a button-operated software menu system. Later versions, which supported audio and communication functions, were moved to the center console and/or operated by a touchscreen, depending on the OEMs human-machine interface (HMI) concept. This development steadily led to unique integrated solutions for each brand as well as unique mobile navigation systems.

There were various efforts to design integrated driver interfaces for in-vehicle information and other existing in-vehicle systems (audio and climate) as the number of functions was increased. Toyota developed the integrated joystick (Toyota Ardeo 1998). BMW introduced i-Drive. Mercedes introduced Command. Audi introduced MMI (Multi Media Interface) as well (2001), which similarly included interaction using a rotary control knob in the center console [63]. Nissan introduced its integrated driver interface in the same year (Figure 12). The position of a central information display close to the windscreen became common at the end of the 1900s.

As with other decades in the USA, the 90s was not without its media controversies over crash risk, the most noteworthy of which was the 1977–1983 CK pickup, the most popular vehicle sold by General Motors. In a very dramatic



(a) (b)

Figure 11: Early car navigation systems (Toyota 1987 (a) and BMW 1994 (b)).

Toyota Ardeo 1998 Nissan Primera 2001 BMW i-drive 2001

(a) (b) (c)

Figure 12: Controls for in-vehicle information systems.

presentation on NBC's *Dateline* in 1993, a very popular news investigative show, a CK was shown being struck in the side and bursting into flames. The allegation was that the fuel tanks, mounted outside the frame rails, were vulnerable and could lead to fires if struck. Interestingly, careful investigation by General Motors found that the crashes had been staged, and rocket igniters had started the fires. In response, NBC retracted the story and paid General Motors for the cost of their investigation [90]. This was a huge blow to the news media and reduced its influence in advocating for auto safety.

Until 1990, the driver was regarded as an element of the driver-vehicle system, interacting with the vehicle by operating the steering wheel and pedals to manage the primary driving task. When a navigation system was installed inside the vehicle, the driver had to perform not only vehicle-control tasks by operating the vehicle, but also navigation tasks. When drivers used a paper map, reading the map while the vehicle was in motion was not easy. Often drivers had to stop the vehicle and read a map to find their way to a destination. When a navigation system was installed inside the vehicle, and the system indicated where to turn, the navigation task could easily be performed in parallel with driving tasks (i.e., a dual-task condition).

Concerns about excessive task demands led to studies of mental workload, human cognitive activity, and what is now commonly known as driver distraction. The 1990s saw the delivery of such guidelines as JAMA Guidelines (version 1.0 in 1990, and version 2.0 in 1999), UMTRI Guidelines (1993) [91], TRL Checklist (1999) [92], HARDIE Guidelines (1996) [93, 94], German Code of Practice [95] and other guidelines in Europe [96]. They gave descriptive principles for designing in-vehicle information systems. Also, relevant ISO activities were initiated to develop standardized evaluation methods and formulate minimum standards for in-vehicle HMIs [97].

Studies by Wierwille et al. and Zwahlen et al. in the previous decade suggested that glancing behavior could be an objective measure of driver distraction [98, 99]. Eye-glance evaluations are most readily conducted for information systems that have been developed and are available for on-the-road use. However, the systems must be assessed during the development. The occlusion device developed by Senders in the 1960s (see Figure 9) to measure visual demand in driving was used to simulate glance behavior during driving [100, 101]. Studies using the occlusion method with liquid-crystal shutter goggles were conducted under the aegis of the Alliance of Automotive Manufacturers (AAM) (USA),

Figure 13: Occlusion method with the shutter goggles.

ISO/TC22/SC13/WG8, and the Japanese Automobile Manufacturers Association (JAMA) to assess the level of distraction caused by visual-manual tasks and their degree of interruptibility (Figure 13) [102]. This method was internationally standardized as ISO 16673 in 2007 [103] based on input of the Advanced Driver Attention Metrics (ADAM) and Adaptive Integrated Driver-vehicle interface (AIDE) projects among others. In 2004, JAMA delivered JAMA Guideline version 3.0, which prohibited tasks that required a total glance time of more than 8 seconds [102]. SAE Recommended Practices J2364 (15-Second Rule and another occlusion procedure) [104], SAE J2365 [105] (task time estimation), and other procedures were also published as a result. In the search for entry methods that were less demanding than visual-manual interfaces, speech interfaces were examined [106, 107].

Several international design guidelines for in-vehicle information systems have been developed mainly in ISO/TC22/SC13/WG8 since 1994. Published standards were ISO 15005 (dialogue management) and ISO 15007 (measurement of visual behavior) in 2002, ISO 15008 (visual presentation) in 2003, ISO 17287 (suitability of TICS while driving) in 2003, ISO 15006 (auditory information) and ISO TR 16951 (criteria for determining priority of messages) in 2004 [108–112]. ISO 26002 (simulated lane change test, LCT) was published in 2011 for assessing driver distraction based on research from the ADAM project in Europe [113]. LCT was developed to evaluate visual manual secondary tasks but also cognitive loading tasks that used speech interfaces or involved phone conversations [114]. Burns et al. give an overview of the relevant evaluation methods [115].

Driver information systems have been developed as research projects since the 1970s and yielded commercial products such as car navigation systems in the 1990s. During their development, researchers were aware of the importance of human factors because using driver information systems while driving was quite different from using conventional in-vehicle equipment, with some ideas from studies of human-computer interaction for office work providing useful insights. In contrast to conventional in-vehicle systems, drivers could be confronted with a large amount of real-time information with which they interacted while driving. Measurement techniques for mental workload, glancing/visual behavior, and task demand developed in the last decade were applied to assess the amount of effort to use these driver information systems. Human factors researchers also played important roles in establishing guidelines and standards that offer principles for designing the systems in advance and evaluation methods accompanying the development process. Having guidelines and standards that were publicized by common agreement facilitated entrenching this technology in society.

4.2. Human Factors Research for Advanced Driver-Assistance Systems. The 2000s were another decade in which crash safety received attention in the news media in the USA. High-profile media stories included (1) rollovers of Ford 15-passenger vans (picked up by several television programs), (2) rear-end crashes and subsequent fires involving 2005–2007 Ford Crown Victorias (commonly used as police cars), picked up by both NBC *Dateline* and CBS, and (3) rollovers of the 1998–2001 Ford Explorer. The Explorer received the most attention, including a segment on 60 Minutes and an entire hour on the PBS Frontline program (http://www.pbs.org/wgbh/pages/frontline/shows/rollover/etc/script.html, http://www.pbs.org/wgbh/pages/frontline/shows/rollover/etc/video.html). The Explorer problem was a combination of a high center of gravity combined with a narrow track width, along with failures of particular Firestone tires, which resulted in rollovers [116, 117]. One of the consequences of this matter was the passage of the US government's Transportation Recall Enhancement, Accountability and Documentation (TREAD) Act, which led to new tire-labeling standards, requirements for tire-pressure monitoring systems, and other changes.

Automobile safety technology began with efforts to reduce the consequences of crashes, by designing vehicles that would be less lethal when struck. Over time, there has been somewhat of a shift in human factors research towards active safety, seeking ways to prevent crashes.

The antilock braking system (ABS), first introduced in 1970, marked the formal beginning of active-safety technology. In 1990, electronic stability control (ESC) and vehicle stability control (VSC) came into widespread use. Adaptive cruise control (ACC) systems, which allow a vehicle to follow the preceding vehicle automatically by maintaining a preset time gap, were introduced by the end of the 1990s [118–120].

In addition, backup monitors utilizing the navigation system's display were introduced in the 1990s to reduce backing crashes. The 2000s saw the introduction of lane-keeping systems, which assist drivers by steering to help them stay in the lane (Nissan 2001), and the collision-mitigation braking systems, which intervene with active braking when distance-sensor data indicates that a collision is unavoidable. These systems are an extension of lane-departure warning systems and blind-spot warning systems. Recent entries into the market are the lane-change decision-aid systems, which provide warnings when the driver begins to change lanes, but another vehicle is in the adjacent lane.

Projects such as INTERACTIVE, SAFE-SPOT, and PREVENT deployed the advances in advanced driver-assistance systems (ADASs) and developed human-machine-interaction approaches for assisted driving. These European initiatives were accompanied by national research programs. In Germany, examples of these include MOTIV (1996–2000), INVENT (2001–2006) AKTIV (2006–2010), SIM^{TD} (2008–2013) and UR:BAN (2012–2016). A major achievement of these projects was intense cooperation between European OEMs, suppliers, and university researchers. Similarly, there has been a series of ASV (Advance Safety Vehicle) projects in Japan (ASV1 (1991–1995), ASV2 (1996–2000), ASV3 (2001–2005), ASV4 (2006–2010), ASV5 (2011–)), involving collaboration between the government and car manufacturers.

As part of the research on ADAS, there were a number of new measures of driving performance developed for car following (time headway, THW) [121, 122], lane keeping (time-to-line crossing, TLC) [123, 124], and braking maneuvers (time to collision, TTC) [125–127] over this decade and prior decades.

If several ADASs are installed in a vehicle, various warnings and other information will be given to the driver. In complex driving situations, multiple warning signals may occur simultaneously. In such cases, the driver may become confused and be unable to respond to the warnings or may not react appropriately. Therefore, warning signals should be integrated (ISO TR 12204) [109, 128].

An important human factors element of ADAS as assistive technology is the relationship between the driver and the system and especially the human-machine interface. In many cases, the driver receives feedback on the system state via the speedometer-tachometer cluster, center console displays, or a HUD, supplemented by force feedback from the steering wheel and pedals. If the driver does not comprehend the system's behavior as it actually is, "automation surprise" occurs when the system behaves unexpectedly. Therefore, interaction concepts for these systems have to take into account phenomena such as "over trust" and "over reliance" on the system to avoid serious problems [129]. Currently, numerous ADASs are available as mature products to support longitudinal and lateral vehicle control. Over time, the control authority of these systems has increased, and more complex, cooperative systems have been investigated [130–132]. How to integrate several ADASs and driver information systems has also been the topic of research [133, 134].

By definition ADASs are intended to assist drivers, so these systems must be designed to be compatible with driving behavior. An ADAS that does not consider driver ergonomic requirements may increase the risk of a crash, even though its aim is to enhance safety. Human factors research is necessary to understand how drivers behave with or without the systems in an actual road environment, not in a laboratory experiment. The research methods described in the next section are necessary for such research.

4.3. Naturalistic-Driving Studies and Driving Simulator Studies. One of the research developments of the 1990s has been the completion of several naturalistic-driving studies as knowing what normally happens on real roads is necessary when developing ADASs. If driving situations are known to be dangerous, then the type of ADAS that should be developed for safety assistance is readily determined. Also, quantitative analysis of driving behavior on actual roads is beneficial for developing vehicle-safety technologies, as well as for developing future driver-assistance systems.

Traditional human factors studies involving controlled experiments are relatively low cost. On the other hand, one cannot conduct a naturalistic-driving experiment of any size for less than $10,000,000, and many cost much more. For that price, one could conduct 20–100 driving simulator experiments, depending upon their complexity. Until the 1990s, there was not sufficient interest in the topics that naturalistic-driving studies address to find funding for them.

Second, naturalistic-driving studies require compact data-collection hardware, low power, a large amount of data-storage capability, and sophisticated wireless communication, so that highly reliable and readily accessed data can be collected. Before the 1990s, that technology did not exist.

In the USA, the National Highway Traffic Safety Administration (NHTSA) conducted the 100-Car Naturalistic-Driving Study in 2001. They collected data on vehicle behavior, road-traffic conditions, and driver behavior in accidents and near-accident incidents, using vehicle-acceleration data as the trigger for recording. This study demonstrated that various distracting situations lead to traffic accidents in the real world [135]. Other relevant studies include the Advanced Collision Avoidance System (ACAS) [136], RDCW [137], and IVBSS [138] projects. Easily installed driving recorders for general-use passenger vehicles became commercially available in Japan in 2003. Detailed causal analysis of accidents and near accidents became possible with this device. JSAE has examined data gathered by driving recorders installed in taxis [139]. They conducted statistical analyses to classify the causes of accidents and also identified specific situations in which drivers committed behavioral errors.

The New Energy and Industrial Technology Development Organization (NEDO) of Japan conducted a three-year project beginning in 2001 to collect driving-behavior data under normal conditions, with no accidents, using instrumented vehicles in real road environments, and compiled the results in a database. This driving-behavior database has been publicly available since 2004 and has been used by universities, research institutions, and industry in research and development activities [140].

In Europe, the EURO-FOT (field operational test) study and the Promoting real Life Observations for Gaining Understanding of road user behaviour in Europe (PROLOGUE) project gathered remarkable naturalistic-driving datasets. EURO-FOT focused on the usage patterns considering ADAS and driver information system applications. An important output from EURO-FOT was the so-called FESTA handbook [141], which provides good practice recommendations for conducting naturalistic-driving studies.

For ADASs that assist steering and pedal control, a control algorithm should be developed to match the driver expectations of the system's behavior. If the control algorithm

of ADAS is different from what the driver expects, the driver may feel uneasy and may not use the system. Traditional research methods, designed to repeat a controlled set of conditions so that they can be examined in a cost efficient manner, are an imperfect representation of the real world. For ADAS design, addition information was obtained from naturalistic-driving-behavior studies [142, 143]. To analyze the large data sets from naturalistic-driving studies, specialized statistical-modeling techniques are used [144, 145]. However, prior to applying these methods, the situations and conditions in which the targeted driving behavior occurs must be identified to create the subset of the data desired for analysis.

Improvements in computer-graphics technology and computing performance enabled detailed representation of road structures and traffic-participant behavior. As a result, simulators could be used as tools in driver-behavior research. Using a driving simulator, experiments can be conducted repeatedly, controlling such traffic situations as the positions of other vehicles relative to the subject vehicle. Experiments using a driving simulator are time efficient and do not expose subjects to the risk of real injury in a crash. Taking advantage of these capabilities, researchers are able to analyze the effectiveness of systems being developed and can anticipate potential problems by analyzing drivers' responses to the prototypes [146].

Until the 1990s, driving simulators were only found in a limited number of laboratories, primarily because of their cost. In part this was because rendering of scenes required high-performance graphic processors, and prior to the 1990s systems with adequate performance were specialized and costly. Second, projectors that had adequate resolution and brightness were also quite costly. After the '90s, the simulator hardware components became much less expensive.

Simulators are useful tools for investigating driver behavior. Driving simulators range from those resembling PC games to full-scale driving simulators such as the National Advanced Driving Simulator (NADS) and Toyota driving simulators. Although driving simulators are now commonly used for automotive human factors research, the research must be conducted with a clear understanding of what each simulator is capable of reproducing and to what degree, and with sufficient assessment or validation of the appropriateness of use for the experiment's purpose [147]. New researchers often do not spend enough time to make sure the values of the dependent measures collected are reasonable for real vehicles. A high-quality research program will likely include a balance of simulator experiments and actual road experiments or naturalistic-driving data [148].

Naturalistic-driving studies and driving simulator studies have proven to be powerful tools for analyzing driving behavior, assessing effectiveness, and identifying problems not only of driver information but also of driver-assistance systems. In the past, automotive human factors research typically focused on the relationship between drivers and vehicles. Now, research has gone beyond the human factors laboratories and extended to human behavioral research in the real world.

4.4. Driver Communications External to the Vehicle—Network Service, Mobile Phones, and Internet Access While Driving. The introduction of information-communication technology has been particularly important for driver information systems. The Vehicle Information and Communication System (VICS), which transmits real-time traffic conditions for specific driving regions through FM radio signals and radio/optical beacons, began operating in 1996 in Japan. In Europe, the Radio Data System (RDS), introduced in the 1980s, later became the Traffic Message Channel (RDS-TMC); it conveys traffic information and messages via the FM signal. OnStar, a network service for GM, was started in 1995 in the USA. This was followed by TeleAid in 1997 in Germany, Toyota's MONET in 1997, Nissan Carwings in 1998 in Japan and BMW Assist and Mercedes MBrace in the late '90s. When the driver accesses the remote operations center of one of these systems, the operator assists with the trip according to the driver's request. Analysis of verbal communication between the driver and the operator, such as phrases used, the timing of utterances and pauses, and the number of turns, will provide insights into designing interactive speech systems for driver information systems.

Mobile radio phones installed in vehicles were first developed in 1947 by AT&T, but the service area was very limited and the phone itself was bulky. The A-Netz mobile-phone network started in Germany in 1952. The first cellular network began operating in 1979 in Japan. In the mid-1990s, cellular phones spread rapidly based on the Global System for Mobile communications (GSM) standard, and, not surprisingly, people used the phone while driving. The use of cellular phones while driving soon became a public-safety concern, and using a hand-held cellular phone while driving was forbidden in many European member states in the 1990s, in Switzerland in 1996, and in Japan in 1999 [102]. Use of cellular phones for conversation is also illegal in some states in the USA [http://www.ncsl.org/issues-research/transport/cellular-phone-use-and-texting-while-driving-laws.aspx] and in a number of countries [149]. Hands-free systems for vehicles have since been introduced and have been shown to be less distracting [150]. The nature and extent of the interference of phone conversations while driving continues to be an important research topic [135, 151–154]. Of increasing importance is the effect of using cell phones on situation awareness [155]. Nonetheless, people use phones while driving for many reasons: they may feel that they do not have too much to do, believe driving is wasted time, feel a need to be connected, are bored, or for many other reasons. Use of phones while driving is widespread [156].

Voice communication by phone is one of many ways for people to communicate and interact with each other and with information systems. However, if the in-vehicle system restricts the access to information strictly for safety purposes, drivers might not connect the device to the in-vehicle system, bypassing the restrictions imposed by the vehicle. How to support interaction with data in these devices that drivers need and want while driving without relying on a visual-manual interface needs further human factors research. Interestingly, relative to the amount of research on

phone use in conversation, relatively little research has been done on interaction with the Internet and intelligent systems while driving [157].

Some thought should also be given to what drivers really want or need to know. Qualitative methods for recording and analyzing human behavior in daily life are being developed in the field of sociology [158–160]. Such methods include ethnography, which describes detailed human behavior, and action research, in which the researcher explores problems of a society while acting as a member of the targeted society (See also [161, 162]).

Communication with those outside the vehicle that is not relevant to the driving task can cause driver distraction. Compared with interactions with driver information systems or ADASs, communication through mobile phones and the Internet is independent of the driving itself. Incoming alerts for phone calls, e-mail, and Short Message Service are external system-initiated interactions that occur regardless of the driving situation. There is a basic potential of driver distraction. To avoid this, there is a big potential if communication devices (nomadic devices) are connected to an in-vehicle information system that can control interaction with the driver to support the driver in the management of his workload. Discussions of possible mechanisms and interfaces for managing information to reduce workload and enhance situation awareness of the drivers were reported in the ITU-T FG Distraction activity [163–165]. However, the nomadic device should first be connected to the in-vehicle system, but should not bother the user. Connectivity technologies such as Bluetooth are important enablers here. Human factors research must design the in-vehicle system to give the driver an incentive to connect the device. Targets of human factors research are not only reducing workload and improving ease of use, but also designing system to induce safe driving.

4.5. Vehicle Communications with Other Vehicles and the Infrastructure. At first thought, these communications would appear to have nothing to do with human factors, which would be incorrect. The purpose of these communications is ultimately to deliver information to the driver. A major part of the cost of building systems to warn of and avoid crashes is the sensing systems, the radar, LIDAR, video, and sonar technologies to provide 360 degree coverage to support the driver. These sensors provide information to determine where all the threats are to the vehicle. This requires identifying each target from the background, identifying the type of target it is, and then developing a prediction of its path, which is used to determine if the target will collide with the driven vehicle. For locations where crashes are frequent, embedding sensors into the infrastructure is cost effective. Infrastructure-based cooperative systems were developed in Automated Highway System (AHS) projects (1996–2007) and the Driving Safety Support System (DSSS) project in Japan [166]. DSSS became operational in 2011 as a pilot study [167]. The system detects vehicles that are hidden by road structures at intersections, merging zones, and curves and informs the driver using an in-vehicle display and by voice [168]. An alternative approach is being examined under the UMTRI-led Safety Pilot program [169] and in other connected-vehicle activities. In a connected-vehicle approach, every vehicle, every pedestrian, and some key fixed objects that are part of the road infrastructure continuously transmit radio signals that communicate what they are, where they are, and, if they are capable of moving, how fast and in what direction they are moving. This, when fully fielded, could simplify the collision detection problem and lead to a potentially significant reduction in crashes, if the response to potential collisions is automatic.

What remains unknown is how to get drivers to respond to hazards they cannot see and may not become an imminent threat for some time [170]. How drivers should be warned if some of the broad array of information is unavailable, and when vehicles should take over the primary driving task will be a focus of future human factors research.

4.6. Autonomous Vehicles—Removing the Driver from Control. Until recently, self-driving cars seemed like a futuristic concept. However, with DARPA's Grand Challenge program [171], Google's demonstrations (http://spectrum.ieee.org/automaton/robotics/artificial-intelligence/how-google-self-driving-car-works), and other activities such as Stadtpilot in Germany [172], advances in autonomous vehicles are occurring quickly.

Questions of concern to human factors researchers include the following: When can automation do a better job of driving than a human being? How can drivers be kept informed of the driving situation? How does the hand-over (driver to vehicle, vehicle to driver) occur? How do drivers of nonautonomous vehicles negotiate with the behavior of autonomous vehicles?

5. What Can Be Learned from History?

In general, the introduction of the automobile and the related achievements in human factors can be called a success story, having served as a stimulus for other research domains.

(1) Over time, the human factors focus has shifted from relying on personal experience to relying on research data that eventually led to standards from SAE, ISO, and others. However, as vehicles evolve, there will continue to be a need to conduct research to develop new standards, and to support the design of vehicles. Relative to other fields of engineering, the use of models to predict human performance while driving (except for control theory and workspace layout) has been limited [173]. Research on computational models of the heterogeneous group of drivers as information processors in very different traffic situations is needed as well as a significant effort to build practical tools engineers can use [174, 175]. Given what has occurred in the past, an important step would be incorporating those models in SAE and/or ISO standards.

(2) Over time, the primary problems that human factors experts address have increasingly shifted from physical to cognitive, but the original problems never go away. Early human factors efforts concerned making sure that drivers

could operate controls while providing adequate force to steer and brake. Although power-assist systems have assured braking and steering can be accomplished, questions about the optional human-device transfer function remain, as well as where to place controls so they can be comfortably operated. There are still issues of field of view, seating comfort, and thermal comfort, especially in connection with electric vehicles. Designers still wrestle with these issues and continue to request better data, better models, and better tools.

(3) Over time, there has been a shift in what the driver does. Initially, the driver just steered the vehicle, sometimes assisted by the codriver. Now, the driver controls an array of information and communication systems being assisted by the vehicle. Driver distraction and overload are major concerns. Research on how to coordinate performing the primary driving task and communicate with those outside of the vehicle, or both people and vehicles, are needed. The need for driver assistance is continuously increasing, especially in urban settings.

(4) Over time, developments in the automotive industry related to human factors mirror technology developments in general with a shift from providing basic mobility to concerns about crash protection and fuel efficiency. The early developments were related to the physical structure of the vehicle, the province of the mechanical engineer. More recent developments are the province of electrical and computer engineers. The most recent efforts, such as the nomadic device forum of the AIDE project, have involved engineers who develop nomadic and mobile devices brought into the vehicle. The next phase of vehicle evolution may center on the motor vehicle as a social mechanism, thus involving urban planners, sociologists, anthropologists, and others. One example of this concerns how to support the use of social networks (and what should be supported) while driving.

(5) Over time, evaluation methods have changed. The original human factors work was based strictly on intuition. That was followed by decades of research involving single test vehicles in scripted on-road experiments along with the analysis of crash data, almost exclusively from the USA. In the last few decades, the use of driving simulators in combination with eye tracking, but also laboratory evaluation of interaction concepts, has become much more widespread. The major recent development in methods has been naturalistic-driving studies and field operational tests, providing extensive real-world driving data. What remains unknown is at what point these studies transition from independent evaluations to a continuing data collection effort analogous to crash evaluations. Also unknown is when some country other than the USA will make its crash data publically available on the web. Without such information, research and design solutions will invariably focus on American problems, which may not match the driving situation in other countries.

(6) Over time, the way in which designers and researchers interact has changed. Initially, that occurred though major, large conferences such as the SAE Annual Congress, the TRB Annual Meeting, and others. Increasingly, however, the preferred venues are smaller, more focused meetings concerning automotive human factors in general, or specific aspects of that topic such as Driving Assessment and AutoUI. In addition, an important degree of informal interaction occurs at standardization meetings of various types.

(7) The news media have been a significant factor in bringing issues of crash safety to light, at least in the USA. Fires, crashes in which children are killed, and rollovers invariably get the most attention. At least once every decade there are major questions raised about the safety of at least one vehicle—Chevrolet Corvair, Ford Pinto, GM CK pickup trucks, Jeep CJ-5, Audi 5000, Ford Crown Victoria, Ford Explorer, and so forth. As a result, auto sales plummet for these models, and the manufacturers respond. Not all of the problems receiving attention from them have been genuine. However, at least in the USA, laws have been passed, research funded, and organizations created because of these media investigations.

The role of the news media in the future is uncertain. The USA was traditionally dominated by three television networks—NBC, ABC, and CBS. However, in recent years there has been competition from other networks in the USA, and foreign networks will soon have a greater presence in the USA. The competition has reduced funding for investigative journalism, but in its place, Internet journalism has arisen.

(8) Until now, automotive research and design have been dominated by the USA, Europe, and Japan. However, with China being the largest market for motor vehicles, and a growing market in India, there is the potential for them to be leading contributors to the automotive human factors research and design in the future.

Thus, although many may view traditional motor vehicles as part of an outdated industry, in fact, the industry has continued to evolve, with continuing pressure to introduce new technology into vehicles to increase safety and comfort and to develop cleaner, more fuel-efficient vehicles. However, the challenge the motor vehicle industry faces that the consumer products industry does not face is the high level of reliability and durability required, a concern that dates back decades ago as described in the literature.

As one can tell from the references provided, there has been an abundant and almost overwhelming amount of research conducted on automotive human factors. Those wishing to delve more deeply into the field may wish to begin by considering other overviews of automotive human factors, such as [176–182]. As the field of automotive human factors continues to evolve, it is important for designers, engineers, researchers, and others working on this topic to continue to learn about it. Reading a few papers or taking a human factors class is not enough. To keep informed, one needs to continue reading about the field, attend conferences, and participate in professional activities.

Acknowledgment

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