In-Vehicle Monitoring by Radar: A Review

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***Abstract*—The proliferation of vehicles and a subsequent increase in traffic accidents have led to a heightened focus on driving safety. As a result, various researchers have been examining ways to enhance driving safety in daily life by implementing smart car technology. In-vehicle sensing utilizing radar technology has emerged as a leading method for monitoring the driver's health, emotions, and attention, owing to its numerous advantages over traditional sensors, including the ability to detect subjects through nonmetallic surfaces and the inherent privacy-preserving mechanisms. In recent years, in-vehicle sensing through radar has undergone significant advancements. This article aims to provide a comprehensive survey of the applications, system-level design, and signal processing of in-vehicle sensing through radar. The published works in this field are categorized into three main groups: occupancy detection, gesture recognition, and occupant status monitoring. This article will discuss the highlighted works and their respective advantages and limitations in terms of applications.**

***Index Terms*—Advanced driving assistant systems (ADASs), artificial intelligence, drowsy/distracted driver detection, frequency-modulated continuous wave (FMCW) radar, gesture recognition, left-behind children detection, millimeter-wave radar, occupancy detection, radar signal processing, smart car, vital sign monitoring, wireless sensing.**

I. INTRODUCTION

THE field of in-cabin monitoring is rapidly emerging as a crucial aspect and popular area of study in the realm of smart car technology, both in terms of comfort and safety. This is primarily driven by the increasing amount of time we are spending on our daily commutes. As evidenced by statistics from 2016 to 2017, 87.3% of Americans (age 16 and over) spend an average of 51 minutes per day driving. [1]. This highlights the need for implementing measures to monitor the vital signs and physiological state of drivers and passengers, such as the breathing rate (BR) and the heart rate (HR). Several innovative monitoring technologies have been proposed and developed in recent years. One such technology is radar-based monitoring, which offers two major advantages over conventional camera-based/optical sensors: the ability to detect and monitor subjects through nonmetallic objects [2] and the inherent privacy-preserving nature of its operation [3].

These benefits can be leveraged for applications beyond safety-related ones by continuously monitoring the postures and vital signs of vehicle occupants, such as airbag deployments or the detection of children left behind. This technology can also be used for functionalities such as controlling the air conditioning, gesture recognition for the human–machine interface of the vehicle infotainment system, and advanced health monitoring [3], [4], [5].

There are several technologies available for in-vehicle occupancy detection, among which mechanical sensors that can measure weight, force, acceleration, or pressure are the most commonly used. These sensors can detect the presence and position of the occupants in the vehicle and can also be used to adjust the vehicle's settings, such as airbag deployment, seat belt tension, and climate control [6], [7]. Mechanical sensors can be divided into three

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TABLE I

DIFFERENT IN-CABIN MONITORING APPLICATIONS BY RADAR

Key application	Main approach	Case study	Reference
Occupancy detection	Range-doppler map or time-frequency spectrum	Artificial intelligence to detect occupied seats	[3], [11]–[34]
	The amplitude of reflected signals	Left-behind child	[2], [35]–[48]
	BR and HR difference	BR and HR estimation	[49]–[51]
Gesture recognition to assist drivers	Micro-doppler features	Artificial intelligence to detect gestures	[52]–[59]
Occupant status monitoring	BR and/or HR estimation	None	[60]–[77]
		Sensor placement for accurate BR estimation	[78]–[80]
		Vital sign monitoring in an ambulance	[81]
		Drowsy driving detection	[82]–[87]
		Biometric driver seat	[79]
		Angry driver	[88]
		Multiple targets vital sign monitoring	[89], [90]
		Car vibrations suppression	[62], [91]–[93]
	Changes in the reflected power	Distracted driver detection by cellphone	[82]
		Random body movement cancellation	[62], [80], [94]
		Airbag	[95]
	Range-doppler map	Distracted/drowsy driver based on head motion	[96]–[101]
	Range doppler map, Changes in the phase of signals	Drowsy driver based on eye blink frequency	[102]–[107]

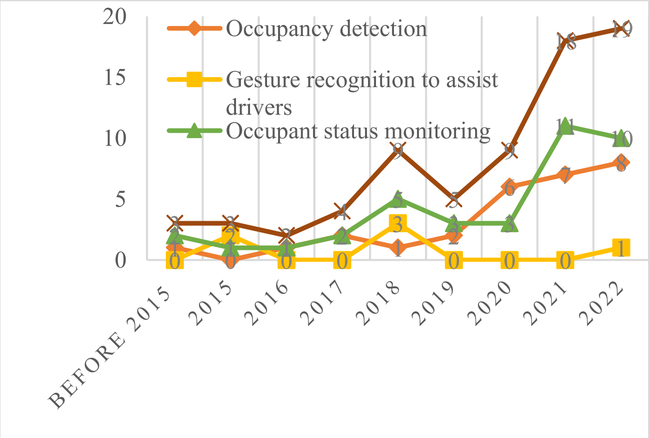


Fig. 1. Distribution of different applications in recent in-cabin indexed papers on Google Scholar by radar over the years.

common categories, including resistive [8], inductive [9], and capacitive [10]. Both resistive and inductive sensors have difficulty discriminating between humans and objects [3]. Capacitive sensors that can detect the dielectric dispersion effects on human tissues are prone to high false detections [18]. Camera vision [108], [109] and infrared (IR) sensors [110] are also commonly used. Although these sensors are more reliable, they lead to privacy issues. Moreover, they are sensitive to sunlight and illumination levels. To overcome these issues, radar can be employed.

As noted earlier, radar-based sensors are one of the most promising ways to address the issues of dead spots in camera vision and dependence on environmental factors. This is why radars are now often explored to monitor people in different places, such as elderly homes, vehicle cabins, and hospitals [111], [112], [113]. In automotive, Hyundai and Toyota have reportedly developed a radar-based monitoring system able to detect in the rear seat dead spot whether children have been left behind [114], [115]. The consumer electronics show in 2023 showed a trend of many new radar variants under development for in-cabin sensing.

Table I represents various key applications of radar inside a vehicle based on the indexed papers and patents found on Google Scholar. Fig. 1 also displays the distribution of indexed papers on Google Scholar across different applications. The number of papers on occupant status monitoring and occupancy detection has increased in recent years. Occupant status monitoring is the most studied application as research on driver health monitoring can help prevent car accidents. The primary approach in this application is to estimate BR and HR. Most studies have focused on accurate BR and HR estimation. However, making a decision after BR and HR estimation can be more beneficial. One of the benefits of in-cabin radars is to detect drowsy drivers by identifying low BR or apnea [83], [86], [107]. According to statistics, almost 30% of fatal car accidents involving deaths are caused by drowsy drivers [83].

In the application of occupant status monitoring, the estimation of BR is a crucial aspect. As depicted in Fig. 2, two different types of techniques can be employed: contact and noncontact techniques. Different contact and noncontact techniques, as well as their technologies, are demonstrated in Fig. 2. For more details, refer to [116] and [117]. Contact techniques, such as sound sensing, which is one of the earliest forms of contact-based medical tests, suffer from a lack of accuracy and are unable to provide proper continuous monitoring [118], [119]. Another technique for BR estimation using contact sensors is the temperature sensing approach, which measures the temperature differential between the air being inhaled and exhaled by a person. One way to implement this approach is by using a thermistor, a type of resistor that changes its resistance with temperature, placed under the nose of the person [120]. Another approach that can be used to estimate BR is the pressure-sensing approach, which leverages

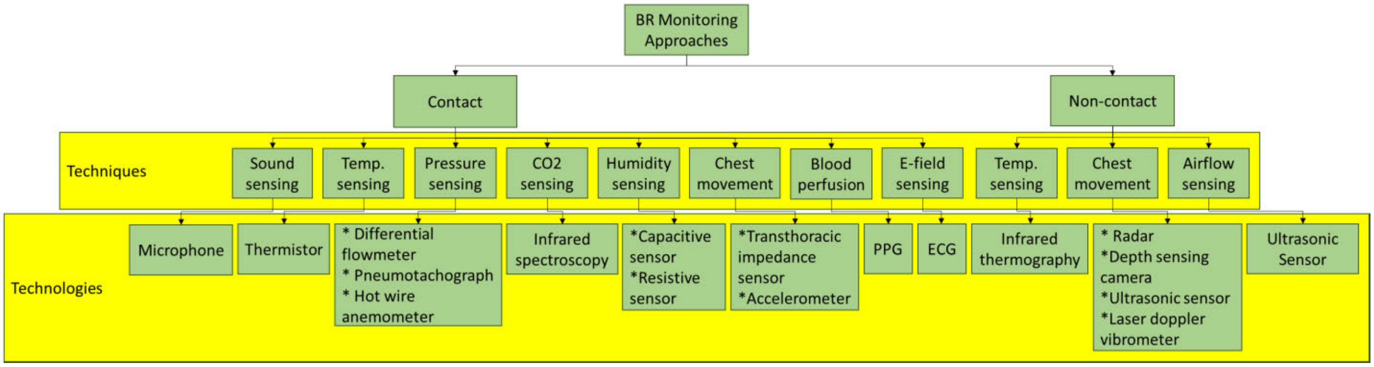


Fig. 2. BR monitoring techniques [116], [117].

the changes in air pressure caused by breathing around the nose. In this approach, a pressure sensor is placed near the nose, and as the person breathes, the airflow causes the sensor to deform, resulting in a variation of its resistance and a corresponding linear change in the sensor output voltage. This change in voltage can then be used to estimate the person's BR [121]. In another method, the amount of carbon dioxide (CO_2) that a person has exhaled will be used for BR estimation. The most used technique for calculating the quantity of CO_2 in gas samples is IR spectroscopy [122]. Another contact-based technique for estimating BR is based on the comparison of the humidity levels between inhaled and exhaled air. In this approach, a humidity sensor is positioned close to the patient's nose or mouth. The exhaled air is more humid than the inhaled air, and by monitoring the changes in humidity levels, the sensor can estimate a person's BR [123]. To estimate chest movements, a thin sheet of the piezoelectric substance can be used to quantify how much the body volume changes while breathing [124]. An additional approach for estimating chest wall activity using contact sensors is the use of an accelerometer. By using the accelerometer and/or gyroscope sensors, it is possible to track the movements of the thoracic and/or abdominal cavities to identify breathing activity. The output of the accelerometer is typically a time series of the acceleration of the chest in three dimensions, which can be processed to extract breathing-related information, such as BR, breathing depth, and breathing patterns [125]. A noncontact, noninvasive technique used to measure blood perfusion across tissues is known as photoplethysmography (PPG). In this technique, IR light is used to illuminate blood vessels, typically by shining it through a patient's finger. The amount of IR light that is reflected or absorbed by the blood is then measured by a PPG sensor, which provides information about changes in blood volume. This information can be used to estimate HR and other vital signs, and to detect changes in blood flow caused by various physiological and pathological processes. PPG is a widely used technique in medical research and clinical practice, and it has been implemented in a variety of devices, including pulse oximeters, wearable devices, and remote monitoring systems [126]. Electrocardiography (ECG) that tracks the electrical field in the chest that the heart and breathing make [127] is another common contact-based approach.

Noncontact sensors are the second type of sensor used to estimate BR accurately. One such approach is IR thermography, which is a noncontact method of measuring BR. The temperature near the nostrils changes during the breathing cycle, and IR thermography can detect these changes in temperature. Specifically, the temperature near the nostrils is 31.17 °C during inspiration and 31.44 °C during expiration. By tracking these temperature changes, IR thermography can be used to estimate BR. This method is nonintrusive and can be used to measure BR in a variety of settings, including in vehicles [128]. Analysis of chest movements in various regions of interest on an image recorded by a video camera can be used to estimate BR [129]. However, this approach triggers numerous privacy concerns.

Another noncontact-based technique for estimating BR is ultrasound. This technique utilizes the sensor's attenuation characteristics to calculate the sensor's distance from the subject, and the phase of the detected peak is then used for the BR estimation. Ultrasound is a noninvasive method that uses high-frequency sound waves to measure distance and detect changes in the position of a subject. It can be used to estimate BR by measuring the expansion and contraction of the chest caused by breathing, medical facilities, and in other environments where contact-based sensors may not be practical or desirable. Ultrasound acoustic waves are unfortunately unable to travel over great distances and can be quickly disrupted by mechanical motion [130]. Hence, ultrasound is not a good selection for in-cabin monitoring applications.

The reflected signal from the human torso can be processed to estimate chest wall vibration without any devices attached to the human body [131], [132]. This level of comfort is a key benefit of contactless sensors over contact ones. In general, contact sensors require a smart wristband, chest straps, or compression garments to be worn. Wearable devices are less convenient because they must always be attached to the human body. As a result, contactless solutions, most of which employ ambient wireless signals [62], are more comfortable for long-term health monitoring [81].

Table II compares different BR monitoring techniques. This evaluation is based on some factors that can be applied for continuous monitoring. In [82], it is concluded that a radar sensor is the best solution inside a vehicle, especially because

TABLE II
COMPARISON BETWEEN DIFFERENT BR MONITORING TECHNIQUES [116]

Method	Integrated solution	Installation on the body	The comfort level for continuous monitoring	Privacy issues	Cost issue
Sound sensing	No	Direct contact	High	Yes	No
Temperature sensing	No	Direct contact	Low	No	No
CMOS MEMS-based	Yes	Direct contact	Low	No	Yes
CO_2 sensing	No	Direct contact	Low	No	No
Humidity sensing	No	Direct contact	Low	No	No
Piezoelectric transducer	Yes	On a dress or a bed mattress	Low	No	No
Accelerometer	No	Direct contact	Low	No	No
Impedance fluctuation sensing	No	On a dress or chair	High	No	No
Infrared thermography	No	No contact	High	Yes	No
Ultrasound	No	No contact/ contact	High	No	No
Radar	Yes	No contact	High	No	No

of its comfort level and protection of privacy. The phase shift of Doppler radars can detect human body vibration. As a result, chest wall displacement caused by breathing and heart vibrations can be sensed to monitor people's health inside a car.

Several review papers on healthcare applications of radar exist. In [116], various breathing monitoring techniques are investigated, and the advantages of using radar technology over other types of contact and noncontact sensors are explained. In [133], [134], [135], [136], and [137], a comprehensive study on vital sign monitoring by radars is provided, and the challenges in signal processing algorithms and hardware are discussed. In [138], recent papers on vital sign monitoring by multi-input–multi-output radars are reviewed, and the challenges of different environments are discussed. In [136], recent papers on self-injection locked radars for vital sign monitoring are surveyed. In [139], state-of-the-art radar papers for obstructive sleep apnea detection are reviewed, particularly system fundamentals and signal processing. To the best of our knowledge, although there are several review papers on recently published vehicular radar papers [140], [141], [142], [143], [144], [145], [146], none of the recent review papers have studied state-of-the-art papers for in-cabin applications. This article reviews recent investigations and industries into different applications of radar in a vehicle, particularly in-cabin applications, and discusses their advantages and limitations in various subjects. This review may help researchers analyze the limitations and gaps in these methodologies, allowing for additional research opportunities.

The remainder of this article is organized as follows. Section II introduces related radars in the market. Section III discusses different applications of radars for inside vehicle monitoring. Finally, we conclude this article in Section IV.

II. AVAILABLE RADARS IN THE MARKET

Different companies employ several distinct types of radar systems in various noncontact sensing applications. Among those that make use of frequency-domain-based systems are continuous wave (CW) [147], frequency-modulated CW (FMCW) [148], [149], [150], or time-domain-based systems invoking ultrawideband (UWB) signals [151], [152], [153], [154], [155], [156], [157]. These systems are frequently utilized in various noncontact sensing situations [158], [159], [160]. FMCW radar has gained popularity in different applications inside or outside of vehicles in recent products mainly due to its low-cost architecture [148], [149], [150].

The utilization of compact radar systems in various companies globally is demonstrated in Table III. This table highlights the utilization of three primary frequency bands, namely, 24, 60, and 77 GHz, for both internal and external cabin applications. Of these frequencies, 24 and 77 GHz are commonly utilized in external cabin applications. In recent years, there has been a shift toward the utilization of 77-GHz FMCW radar systems, as they provide a wider bandwidth, enhanced range and velocity resolution, and a more compact antenna array in comparison to 24-GHz systems. This trend is indicative of the industry's inclination toward the implementation of 77-GHz radar technology [161]. The utilization of 60-GHz radar technology is primarily confined to applications within the cabin. The utilization of distinct frequency bands for internal and external cabin applications is a strategic measure to mitigate the potential for interference and ensure optimal performance of the radar systems.

III. DIFFERENT APPLICATIONS OF RADARS INSIDE A VEHICLE

A. Occupancy Detection

The importance of occupancy detection by radar is further accentuated within the context of a vehicle. The detection of occupants is a crucial step as it enables other applications such as status monitoring to be activated [3]. This is due to the high computational cost associated with vital sign estimation. Therefore, when a seat is unoccupied within a vehicle, it is unnecessary to apply vital sign estimation, reducing computational cost and increasing system efficiency.

Researchers have proposed some assumptions for occupancy counting by radars. Most in-use systems have been evaluated with groups of individuals that were well-spaced apart from one another in a wide area. In addition, the locations of the individuals were not determined, and some systems could only estimate the number of people. Hence, most existing approaches for estimating the population in a large space using radars need quite complicated signal processing techniques that result in high computational costs [3].

TABLE III
DIFFERENT RADAR COMPANIES FOR INSIDE AND OUTSIDE OF CABIN

Manufacturer	Country	Applications for inside and outside of cabin	Reference
Acconeer AB	Sweden	• Occupancy detection • Gesture control	[165]
Ainstein	USA	• ADAS • Blind spot detection	[166]
Analog Devices	USA	• ADAS	[167]
Ancortek	USA	• Gesture Recognition	[168]
Aptiv	USA	• ADAS	[169]
Arbe	Israel	• ADAS	[170]
Autoliv	Sweden	• ADAS • Blind spot detection • Smart airbags	[171]
Bitsensing	South Korea	• ADAS • Traffic monitoring	[172]
Bosch	Germany	• ADAS • Automatic emergency braking • Adaptive cruise control	[173]
BYDA	South Korea	• Vehicle detection system • Speed enforcement system • Vehicle speed detection • Red-light enforcement System • Stop line detection • Blind spot detection • Adaptive intersection light control	[174]
Calterah Semiconductor Technology	China	• ADAS • Automatic emergency braking • Front collision warning • Blind spot detection • Child presence detection	[175]
Continental	USA	• ADAS • Automatic emergency braking • Adaptive cruise control • Vehicle speed detection • Traffic jam assist	[176]
Denso	Japan	• ADAS • Automatic emergency braking • Adaptive cruise control	[177]
Echodyne	USA	• ADAS	[178]
Farran	Ireland	• Intelligent Transportation Systems	[179]
Fujitsu	Japan	• Vital sign monitoring	[180]
Gapwaves	Sweden	• ADAS	[181]
General radar	USA	• ADAS	[182]
Ghostwave	USA	• ADAS	[183]
Hella	Germany	• ADAS • Blind spot detection	[184]
Hitachi	Japan	• ADAS	[185]
Houston Radar	USA	• Traffic monitoring	[186]
Hyundai Mobis	South Korea	• ADAS	[187]

A simple approach by radar for occupancy detection is to count individuals entering and leaving at the entrance. In [162], [163], and [164], it is demonstrated how to count several persons moving through a broad entrance or passageway at once. Their suggested approaches relied on patterns of received signals according to the population, while the radar was mounted at a height of 2.3 m on the roof to cover a large area. This methodology employs a simpler approach to counting occupants.

There are three main approaches by radar inside a vehicle cabin for occupancy detection. In the most common approach, researchers rely on the extracted features from micro-Doppler signatures [3], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21]. This approach employs artificial intelligence to detect and classify occupied seats after feature extraction. In fact, these features are fed to artificial intelligence to be used in classification. These signatures can also appear in different other types of data like time–frequency [12], [13], [14], [19], [21].

On the other hand, other researchers employed the reflected energy to detect occupancy. The most common usage for this approach is the left-behind children detection to save

TABLE III
(Continued.) DIFFERENT RADAR COMPANIES FOR INSIDE AND OUTSIDE OF CABIN

Manufacturer	Country	Applications for inside and outside of cabin	Reference
IEE Smart Sensing Solutions	Luxembourg	• ADAS • In-vehicle sensing	[46]
Infineon Technologies	Germany	• ADAS • Blind spot detection • Driver monitoring system • Vital sign monitoring • Child presence detection • Gesture recognition	[26]
InnoSenT	Germany	• ADAS • Automated trunk and door control • Front collision warning • Child presence detection • Occupancy detection • Vital sign monitoring	[45]
Kestrel Radar Sensors	UK	• Traffic monitoring	[188]
Lunewave	USA	• ADAS	[189]
Magna	Canada	• ADAS • Automatic emergency braking • Automated parking • Rear seat monitoring • Gesture recognition	[190]
Mando	Canada	• ADAS	[191]
Metawave	USA	• ADAS • Blind spot detection • Front collision warning • Automatic emergency braking	[192]
Mobileye	Israel	• ADAS	[193]
Neteera	Israel	• Occupancy detection • Vital sign monitoring	[194]
Nidec-Elesys	USA	• ADAS • Automatic emergency braking • Adaptive cruise control	[195]
NOVELDA	Norway	• Occupancy detection • Vital sign monitoring • Child presence detection	[196]
NXP Semiconductors	Netherlands	• ADAS	[197]
Oculii	USA	• ADAS	[198]
OmniPreSense Corporation	USA	• Traffic monitoring	[199]
Radsee	Israel	• ADAS	[200]
Renesas	Japan	• ADAS	[201]
RFbeam Microwave	Switzerland	• ADAS • Enforcement sensors	[202]
Silicon Radar GmbH	Germany	• Gesture recognition for touchless display control • Driver alertness • Occupancy detection • Automated trunk and door control • Roadway inspections while driving	[203]
Smart Radar System	USA	• ADAS • Occupancy detection • Driver monitoring system • Child presence detection	[204]
Socionext	USA	• Human machine interface	[205]
Staal Technologies	Netherlands	• Occupancy detection	[206]
Steelmate	China	• ADAS	[207]
Steradian Semiconductors	India	• High resolution automotive radar • Smart sensing • Precision parking	[208]

TABLE III
(Continued.) DIFFERENT RADAR COMPANIES FOR INSIDE AND OUTSIDE OF CABIN

Manufacturer	Country	Applications for inside and outside of cabin	Reference
STMicroelectronics	USA	• ADAS • Automatic emergency braking • Adaptive cruise control	[209]
TeraSilIC	Taiwan	• Hands-free tailgate release • Liveness detection in cars	[210]
Texas Instruments	USA	• ADAS • Adaptive cruise control • Automatic emergency braking • Front collision warning • Traffic jam assist • Automated parking • Monitor occupant status • Occupancy detection • Gesture recognition	[24]
Tung Thih	Taiwan	• ADAS	[211]
Uhnder	USA	• ADAS	[212]
Vayyar	Israel	• Intelligent Transportation Systems • ADAS • Automatic emergency braking • Occupancy detection • Smart airbags • Vital sign monitoring • Child presence detection • Intrusion detection	[23], [44]
Veoneer	Canada	• ADAS • Blind spot detection • Adaptive cruise control • Automated trunk and door control • Front collision warning • Automatic emergency braking • Child presence detection	[213]
Xandar Kardian	Canada	• Driver monitoring system • Occupancy sensors	[214]
Zadar Labs	USA	• Autonomous vehicles and trucking	[215]
Zendar	USA	• ADAS • Automatic Emergency Braking • Adaptive cruise control • Front collision warning • Blind spot detection	[216]
ZF Friedrichshafen AG	Germany	• ADAS • Automatic Emergency Braking • Adaptive cruise control • Front collision warning	[217]

children and pets, and avoid death in excessively hot or cold conditions [2], [14], [35], [36], [37], [38], [39], [40], [41], [42], [43]. Some studies have used this approach to detect a single occupied seat [62]. These studies focused on driver detection before vital signal monitoring. Finally, in the third approach, researchers proposed to use vital sign signals to count occupied seats [19], [49]. This approach presents the most reliable solution for the left-behind problem.

There are some factors for sensor selection in occupancy detection by radars inside a vehicle. One of the most important factors is frequency selection. As seen in Fig. 3, most in-cabin sensing investigations by radar for occupancy detection have

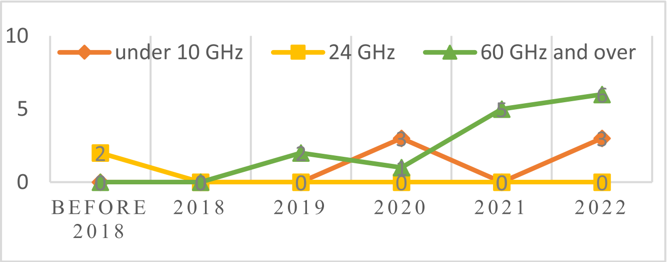


Fig. 3. Distribution of recent studies in frequency selection for occupancy detection inside a vehicle by radar over the years indexed on Google Scholar.

TABLE IV
COMPARISON BETWEEN THE DIFFERENT IN-CABIN PUBLISHED PAPERS FOR OCCUPANCY DETECTION BASED ON SETUP FREQUENCY AND METHODOLOGY BY RADAR

Reference	Frequency (GHz)	Data representation	Approach	Other considerations
[19]	7.29	Spatial-temporal-circulated gray level co-occurrence matrix (STC-GLCM)	Stochastic gradient descent using 3 different classifiers	• Extracted features by singular value ratio from vital signs, including BR and HR
[11]	6.8	Processed raw radar signals	Deep neural network	• The model has been evaluated by changing activation function, the number of nodes in hidden layers, and the number of layers
[20]	6.8	Extracted statistical features from raw radar signals	Bagging with decision tree	• A feature selection approach using neighborhood component analysis used to select best features.
[18]	61	The spectral power and Wiener entropy of processed raw radar signals	Linear discriminant analysis and maximum likelihood estimation	
[3], [15]	77	Range-azimuth	KNN, SVM, and random forest	
[16]	60	Point cloud map	An enhanced Euclidean clustering	• Adaptive monitoring of target presence by an enhanced Euclidean clustering as well as a state machine technique
[2], [14]	77	Processed raw radar signals	KNN, SVM, and random forest	• For the left-behind children detection, a novel approach based on correlation in the time domain has been employed
[13]	2.45	Time–frequency	Binary decision tree	• There are three specific extracted features based on degree of scattering points and vital signs to detect people.
[12]	77	Range-azimuth	SVM	
[21]	60	Time–frequency	AUC, SMD, Bhattacharyya coefficient, and Hellinger distance	
[22]	60	Range-doppler	Regression predictions according to a novel loss function called Label-Aware Ranked loss	
[62]	60	Processed raw radar signals	Standard deviation of the envelope amplitude	
[37], [38]	24	Processed raw radar signals	Cross-correlation	
[39]	80	Processed raw radar signals	Peak detection	• An antenna design for in-cabin sensing
[41]	24	Processed raw radar signals	Peak detection	• A patch antenna design for in-cabin sensing
[36]	0.868			• A patch antenna design for occupancy detection
[40]	24			• Simulation of in-cabin environment to study multipath effect on reflected signals.

used millimeter-wave radar (60 GHz and over). As we discussed earlier, millimeter-wave radar has several benefits over centimeter-wave radars and low carrier frequency radars. Regarding sensor placement, because the radar should be placed under the car roof in occupancy detection applications, the dimensions of the radar package are less important in comparison to vital sign monitoring applications. More details about the recent works can be found in Table IV.

TABLE V
COMPARISON BETWEEN THE DIFFERENT IN-CABIN PUBLISHED PAPERS FOR OCCUPANCY DETECTION BASED ON THEIR ACCURACY OR ADVANTAGES AND LIMITATIONS BY RADAR

Reference	Accuracy or advantages	Limitations
[19]	• In counting the number of occupied seats in a stationary and moving vehicle, the accuracy is 97.5% and 97%, respectively. • A novel feature extraction method based on spatial-temporal-circulated gray level co-occurrence matrix • Collecting a valuable database	• Harmonic analysis might be applied to increase HR estimations. • The BR is assumed to be 12 to 18. However, it could be more than 18 [49]. • The HR is assumed to be 60 to 120. However, it could be more than 120 [49].
[11]	• Classification accuracy by deep neural network: 99.5% • Collecting a valuable database	• The designed radar system works by a single receiver as can be seen in Fig. 4. More receivers could improve target discrimination.
[20]	• Classification accuracy: More than 90%. • A deep investigation on statistical feature extraction	• The designed radar system works by a single receiver. More receivers could improve target discrimination. • Age diversity in experiments
[18]	• The average accuracy of LDA and MLE: 96.14% and 98.88%, respectively.	• The designed radar system works by a single receiver. More receivers could improve target discrimination. • More features could be extracted to enhance results.
[3], [15]	• The accuracy of multiclass classification and binary classification methods: 97%	• Inappropriate model evaluation by k-fold
[16]	• The accuracy of detection in different postures: more than 84% • The accuracy of detection of dynamic experiments: more than 91%	• Lack of details of theoretical approaches
[2], [14]	• The accuracy of occupancy detection is more than 90% • The accuracy of left-behind human detection is 100%	• Lack of details of theoretical approaches
[13]	• The average classification accuracy for a human with or without motion is 98.6%.	• Single person is investigated.
[12]	• The accuracy of occupancy detection in each row of a car is 97.8%.	• The occupancy of detection has not been tested for each seat of a row separately. • Inappropriate model evaluation
[21]	• The performance of the proposed method for passenger detection is validated by an area under the curve greater than 0.98.	• The designed radar system works by a single receiver. More receivers could improve target discrimination. • Harmonic analysis might be applied to increase HR estimations. • The HR is assumed to be 48 to 108. However, it could be more [49].
[62]	• Accurate occupancy detection	• Single seat occupancy detection
[37], [38]	• The sensor is highly robust to noise and environmental influences like traffic or weather, resulting in fewer false alarms.	• Single seat occupancy detection • More measurements are required for evaluation
[39]	• The peak of the reflected signal from a human differs significantly from that of an unoccupied seat. • A unique antenna design for in-cabin sensing	• Single seat occupancy detection • Lack of collected data in real driving environments
[19]	• The accuracy of occupancy detection in a stationary and moving vehicle are 97.5% and 97%, respectively. • A novel feature extraction method based on spatial-temporal-circulated gray level co-occurrence matrix • Collecting a valuable database	• Harmonic analysis might be applied to increase HR estimations. • The BR is assumed to be 12 to 18. However, it could be more than 18 [49]. • The HR is assumed to be 60 to 120. However, it could be more [49].

There are three main approaches by radar inside a vehicle cabin for occupancy detection. In the most common approach, researchers rely on the extracted features from micro-Doppler signatures [3], [11], [12], [13], [14], [15], [16], [17], [18],

[19], [20], [21]. This approach employs artificial intelligence to detect and classify occupied seats after feature extraction. In fact, these features are fed to artificial intelligence to be used in classification. These signatures can also appear in different other types of data like time–frequency [12], [13], [14], [19], [21]. On the other hand, other researchers employed the reflected energy to detect occupancy. The most common usage for this approach is the left-behind children detection to save children and pets, and avoid death in excessively hot or cold conditions [2], [14], [35], [36], [37], [38], [39], [40], [41], [42], [43]. Some studies have used this approach to detect a single occupied seat [62]. These studies focused on driver detection before vital signal monitoring. Finally, in the third approach, researchers proposed to use vital sign signals to count occupied seats [19], [49]. This approach presents the most reliable solution for the left-behind problem.

Table V compares the various in-cabin published papers on occupancy detection using radar, based on their accuracy and advantages and limitations. All the recent investigations have reported accuracy levels above 90%; however, some limitations have been identified, which should be addressed in future publications. One of the most significant limitations is the utilization of inappropriate methods for estimating vital signs in the context of occupancy detection. In [19] and [21], the assumed HR does not cover children's HR properly. The HR of children can be more than 120 beats per minute [49]. In [19], the BR is also considered to be less than 18, while it can be higher for children [49].

One of the issues in using artificial intelligence is the split of the data set into a test set and a training set. In [3] and [12], to train the artificial intelligence approach, all gathered data are pooled and shuffled. This method offered high accuracy. However, Abedi et al. [5] mentioned that the evaluation method cannot be used for new measurements. Since radar has a high frame rate, combining all frames and selecting a part of them to test would not guarantee that the test set was fully invisible to the model.

B. Gesture Recognition

Potential distracting factors for drivers have increased due to crowded roads in addition to the enhanced infotainment functionality and vehicle's ability to interact with its driver. Visual, cognitive, physical, and auditory factors are among the main causes of driving distraction. Visual and physical distractions, when combined, have the biggest impact on driving performance [53]. Researchers have conducted extensive studies to address the aforementioned issues. Noncontact human–computer interaction has been proposed and developed recently, and the topic of contactless human–computer interaction using hand-based gesture recognition has been extensively explored recently.

Several sensors can be employed in hand-based gesture recognition. Camera-based sensors raise privacy concerns and have high computing costs due to considerable signal processing and are sensitive to changes in background color and light intensity [218], [219]. In very dim light conditions, the accuracy rate decreases by 30% [54], [220]. IR sensors can also be employed for hand gesture recognition inside the vehicle. However, they do not preserve privacy and are sensitive to illumination levels [221]. Depth-based sensors are excellent at sensing location changes, but they are unable to identify hand forms or orientations [222]. Wearable technology restricts system input to the person who is wearing the device [53]. Alternatively, radars can identify particular hand and finger movements, and are unaffected by illumination variations while effectively ensuring in-cabin privacy [58]. Recent radar-based gesture recognition investigations have relied on micro-Doppler signatures. These investigations employed either range-Doppler [53], [54] or time–frequency [52], [55], [56], [57], [58], [59].

Despite the benefits of radars, the fundamental issue with radar-based gesture detection systems is their dependence on distance and direction [58]. In [58], the time of arrival (TOA) information has been fed to a learning approach to address this issue, while, in [52], different angles and ranges have been examined. The maximum tilt from the perpendicular angle and the maximum range to have reliable results are 15° and 100 cm, respectively.

The choice of a particular radar system has a direct impact on the efficiency of radar for hand-based gesture recognition. For example, the number of receivers in the radar system determines the angular resolution of the radar. More receiver channels will result in better angular resolution and better discrimination. Lim et al. [11], [20] and Song et al. [21] could use more channels to have better angular resolution and reliable results. However, they have employed a radar sensor with only one receiver to collect data. By one receiver, the FMCW radar cannot discriminate targets located in the same range even at different angles accurately [223]. Another important parameter is the carrier frequency. Recent papers mostly have used millimeter-wave radar to achieve accurate detections. As seen in Table VI, higher frequencies are more sensitive to small radar cross section changes and would have better results [52]. The range resolution of radar is also one of the key factors since better range resolution will result in better discrimination [155].

Gesture recognition becomes more challenging with more gestures. According to studies in Table VI, there are typically seven to eight features for classification and identification. Another important element is the distance of the hand from the radar.

C. Occupant Status Monitoring

Recent investigations mostly focused on occupant status monitoring due to several reasons. Status monitoring is a major factor in assessing a person's health and detecting emergencies due to respiratory distress and heart attacks. Monitoring vital signs such as BR can also reveal crucial information about a person's well-being and may reveal a variety of medical conditions [224]. As the body tries to maintain the amount of oxygen available to the tissues, a change in BR is typically the first indication of a health issue [225], [226]. As driving is increasingly becoming an inevitable part of our day, monitoring a driver's vital signs can allow early detection of health issues. This can lead to improved road safety.

TABLE VI

COMPARISON BETWEEN DIFFERENT IN-CABIN PUBLISHED PAPERS FOR GESTURE RECOGNITION FOR HUMAN–CAR INTERFACE BY RADAR

Reference	Data representation and data dimensions	Approach	Frequency (GHz)	No. of gestures	Hand-to-radar distance (cm)	No. of participants and samples for each gesture
[53]	Range–Doppler (2D)	Random forest	60	6	Not specified	Not specified, 20
[54]	Range-doppler, horizontal angle-range, and pitch angle-range(3D)	3DCNN and series LSTM network	60	8	10-90	4, 1000, (2 seconds each recording)
[52]	Time–frequency (2D)	CNN	77	9	20-100	Not specified, 360
[55]	Time–frequency (2D)	Decision tree	25	6	0-30	4, 60, (4 seconds each recording)
[56]	Time–frequency receiver 1, time–frequency receiver 2, and time–frequency receiver 3 (3D)	3DCNN	24	10	0-50	3, 1714
[58]	Frequency of the reflected signal, Variation of time of arrival, the variance of the probability density function	K-means	6.8	5	0-100	3, 50
[57]	Time–Doppler (2D)	Energy estimation	25	10	0-150	Not specified
[59]	3 extracted features from time-range (the variance of the hand's displacement, the magnitude variance, and the hand's surface area)	Neural Network	6.8	6	Not specified	1, Not specified (10 seconds each recording)

Monitoring a driver also can warn them if they are experiencing stress or sleepiness, which can impact the risk of an accident. [62]. There are some ways to determine if the driver is sleepy. Most papers used HR and BR monitoring. An abrupt decrease in BR and HR is a sign of a drowsy driver [82], [83], [84], [85], [86]. On the other hand, head motion and eye blink frequency also can be monitored to detect sleepy drivers [96], [97], [98], [102], [103], [104], [105], [106], [107]. Recent investigations have mostly used the extracted features from micro-Doppler signatures. In [103] and [105], a 77-GHz radar has recorded signals from eyeblink. They have used ensemble empirical mode decomposition (EEMD) to remove unnecessary information. Based on useful information, the signals were reconstructed and fed to a short-time Fourier transformation. Finally, a cell-average constant false alarm rate (CFAR) has been applied to detect eye blinks. In [106], heartbeat and respiration have been filtered before applying CFAR.

There are many ways to identify distracted drivers by radars. The most common solution is the use of micro-Doppler signatures, especially head motions [90], [91], [92]. In [92], different head motions have been classified based on velocity–time maps by a neural network generated from a millimeter-wave radar at 77 GHz placed in front of the driver. In [90], the range-time maps have been utilized to monitor head movements by a 60-GHz radar. Another common distraction is mobile usage. The distracted driver by mobile can be recognized by scanning the reflected energy over time [76]. Anger issues can also be addressed by radars. Leem et al. [82] have focused on detecting an angry driver. They rely on changes in breathing rhythm and HR. If the detected anger exceeds the threshold value, the device sends a signal to the voice device mounted on the vehicle to play music to relieve anger.

It can be seen in Table I that a large number of recent works focused on measuring BR and HR accurately. Mahler et al. [60], Xu et al. [61], Lazaro et al. [62], Leonhardt et al. [63], Yang et al. [64], Broto [69], and Park et al. [227] used different methods to reach this objective. When it comes to pulmonary diseases, respiratory rates may be used together with breathing patterns to both diagnose and track a person's health concerns. While the average resting respiratory rate varies from person to person, it generally ranges between 12 and 20 breaths per minute [228]. Apnea (cessation of breathing), bradypnea (low respiratory rate), and tachypnea (high respiratory rate) are the three types of abnormal respiratory rates [229].

TABLE VII
COMPARISON BETWEEN THE DIFFERENT IN-CABIN PUBLISHED PAPERS FOR VITAL SIGN MONITORING BASED ON THEIR SETUP, INCLUDING SENSOR PLACE, FREQUENCY, GROUND TRUTH, AND RADAR BRAND AND/OR PACKAGE SIZE

Reference	Sensor place	Frequency	Ground truth	Radar brand and/or package size
[62]	Mobile holder (right side of steering wheel)	60	Air-flow, Temperature sensor	XM132 (25×20 mm)
[65], [69]	In front of the chest of the main subject	60	ECG	XM112
[71]	On the steering wheel	4.3	Edan iM50	Not specified
[78]	Rearview mirror	7.25	A USB pressing button to count breaths as a ground truth	X2M200 (50×70 mm)
[90]	The upper left of the windshield	7.5	Pulse oximetry	X4M300 (50×70 mm)
[89]	In front of the chest of the main subject	77	Pulse oximetry	Not specified
[82]	Under the steering wheel	6.8	Nasal breath sound recordings from a smartphone, ECG (PSL-iECG2)	X2 (50×70 mm)
[83]	The upper left of the windshield	7.29 and 8.748	Pulse oximetry	X4M300 (50×70 mm)
[84]	The lower left of the steering wheel	2.4	Self-assessment of the participant for being drowsy	Not specified
[94]	Behind the seat	60	A pressure sensor is worn on the abdomen	50×50 mm
[80]	Under the steering wheel	77	ECG, Respiration belt	IWR1843BOOST
[79]	Behind the seat	24	ECG	Not specified
[88]	In the driver's seat	Millimeter wave	Camera, Wearable physiological detection instrument	Not specified
[67]	Rearview mirror	77	Polar H10 heart monitor	AWR1642BOOST
[68]	Rearview mirror	120	Spirometer	Not specified
[49]	The left top side of the subjects' chest	60	A clinical reference sensor BSM6501K	IWR6843
[62]	Mobile holder (right side of steering wheel)	60	Air-flow, Temperature sensor	XM132 (25×20 mm)
[65], [69]	In front of the chest of the main subject	60	ECG	XM112
[71]	On the steering wheel	4.3	Edan iM50	Not specified

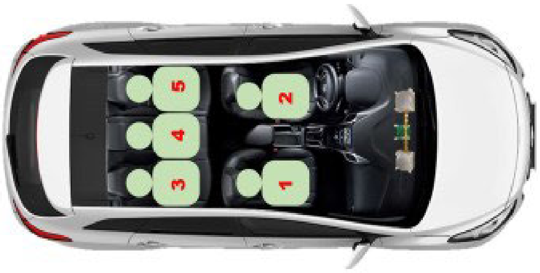


Fig. 4. Radar setup in [11]. Seats 3 and 4 have the same time distance from the radar. The discrimination of these two seats is possible by having more than one receiver.

Other atypical breathing patterns have been documented in [224].

Table VII compares different recent works according to their setup for in-cabin radar applications to monitor vital signs. These papers are compared based on the following criteria: sensor place, frequency, ground truth, and radar brand and/or package size. As apparent from the table, the rear view mirror is the most common place to attach the radar in recent studies. In [78], there is also a deep investigation into sensor placement. The findings indicate that the best place to monitor the driver's BR is in the rearview mirror, as can be seen in Fig. 5.

Most recent works have developed systems to monitor drivers' BR. Hence, the sensor placement is investigated to estimate the BR and HR of drivers accurately. As shown in Table VII, the rearview mirror is the most common place to attach the radar in recent studies. In [78], there is also a deep investigation into sensor placement. The findings indicate that the best place to monitor the driver's BR is in the rearview mirror, as can be seen in Fig. 5.

Frequency selection is also a crucial task to have accurate BR and HR estimations. There are some significant factors in frequency selection. Body surface reflection is the most significant one. Less penetration can reveal better information in vital sign monitoring by radar. In [78] and [230], it is demonstrated that the higher frequencies can penetrate less in the human body. Various experiments were conducted, and it was demonstrated that body motion at high frequencies has a greater impact on signal reflection than the impedance change of the skin surface [107], [231].

In addition, the higher the carrier frequency, the higher the sensitivity of radar on small movements [232]. Hence, radar can estimate human body vibration accurately. However, phase wrapping is more possible in higher frequencies resulting in a more complicated signal processing chain. When the phase of the slow-time signal exceeds the phase range $(-\pi, \pi)$, phase wrapping occurs. Since the chest wall displacement can reach 12 mm and the wavelength of the most commonly used carrier frequency, 60 GHz, is almost 5 mm, this problem can occur frequently [223].

Fig. 6 depicts the distribution of recent studies in frequency selection for vital sign monitoring inside a vehicle by radar over the years indexed on Google Scholar. Recent studies employed millimeter-wave radar (60 GHz and over

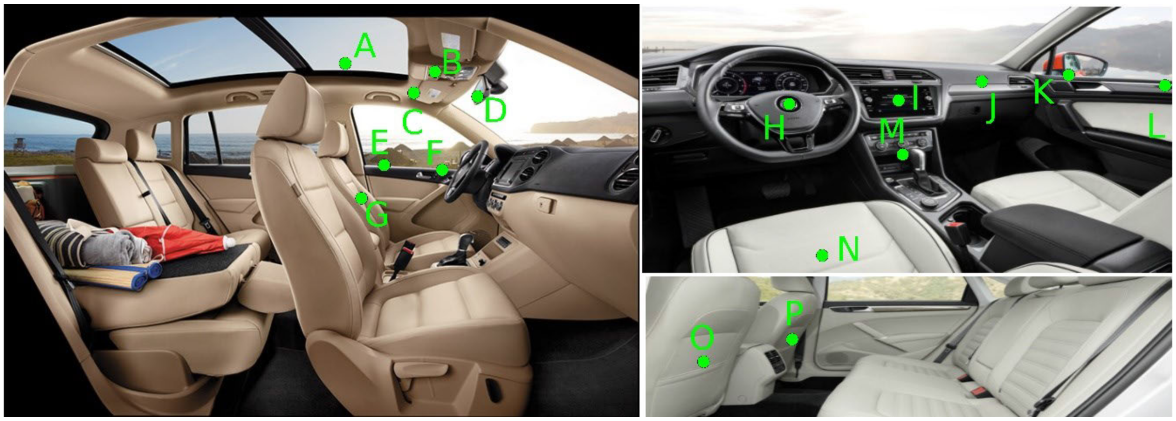


Fig. 5. Different radar placements inside a vehicle for driver's BR estimation [78]. The rear mirror (D) has the best results.

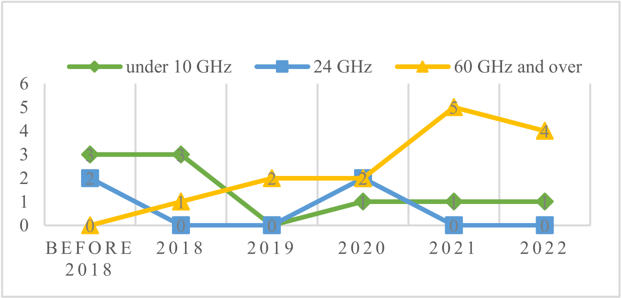
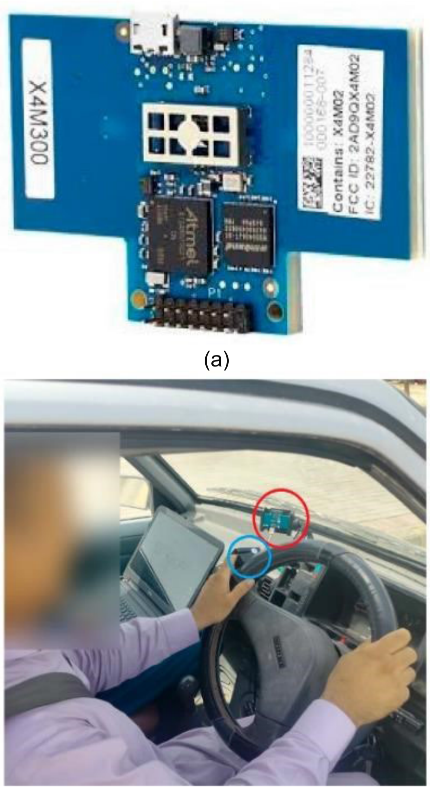


Fig. 6. Distribution of recent studies in frequency selection for vital sign monitoring inside a vehicle by radar over the years indexed on Google Scholar.



(a)

(b)

Fig. 7. X4M300 used in (a) radar board and (b) radar setup inside a car for vital sign monitoring of driver [83].

frequencies) to monitor vital signs inside a vehicle. It is mentionable that the Federal Communications Commission (FCC) is currently emphasizing the 60-GHz band to be used in life-saving applications [233].

Another important factor in sensor selection is package size. The small dimensions of radar for in-cabin applications are essential due to the low space inside a vehicle. Hardware integration is an important consideration to reduce package dimensions. Smaller devices and circuit components can be made by higher carrier frequencies increasing the possibility of hardware integration [234]. Small package radar with dimensions less than 50 × 70 mm was employed in recent investigations. Fig. 7 depicts the board and radar setup inside a vehicle for vital sign monitoring of the driver [83].

Different investigations used different types of ground truths to assess their proposed algorithms for vital sign monitoring inside a car. As can be seen in Table VII, the most common ground truth for the evaluation of estimated HR is pulse oximetry. Fig. 8 shows the pulse oximeter used in [83]. It is a nonintrusive way to measure oxygen saturation, which can lead to estimating BR and HR [89], [235].

There are many considerations to consider while attempting to improve vital sign monitoring accuracy. These include signal processing chain, human body motion cancellation, vehicle vibration cancellation, clutter removal, multipath removal, beam steering, phase unwrapping, and harmonic analysis. Table VIII compares different in-cabin published papers for vital sign monitoring regarding their signal processing chains.

To improve the quality of vital sign signals inside a vehicle, random human body cancellation has been studied [62], [80], [94]. A slow-time envelope modulation results from the breathing-related vibrations of the chest and the random human body motion. The breathing signal can be filtered to prevent significant frequency interferences, but, if there are a lot of random human body motions, the interferences will appear in the breathing frequency range. Intermodulation distortions can also occur in this frequency range [236]. In [94], the driver's motions are calculated

TABLE VIII
COMPARISON BETWEEN THE DIFFERENT IN-CABIN PUBLISHED PAPERS FOR VITAL SIGN MONITORING IN THE SIGNAL PROCESSING CHAIN

Reference	Human body motion cancellation	Car body vibration cancellation	Clutter removal	Multipath removal	Beam steering	Phase unwrapping	Harmonic analysis	Estimation method
[62]	Yes	Yes	Yes	No	No	Not necessary	No	Peak search algorithm in the time-domain
[71]	Yes	No	Yes	No	No	Not necessary	No	Peak of FFT of target's vibration
[78]	Yes	Yes	Yes	No	No	Not necessary	No	Two sequential peak detection on the frequency domain
[90]	No	No	Yes	Yes	No	Not necessary	No	Correlation coefficients
[89]	No	No	Yes	No	No	Yes	No	Peak of FFT of target's vibration
[82]	Yes	No	Yes	No	No	Not necessary	No	Peak of FFT of target's vibration
[83]	No	No	Yes	No	No	Not necessary	No	Peak counting in the time domain
[84]	No	No	Yes	No	No	No	No	Peak counting in the time domain
[94]	Yes	No	Yes	No	No	No	No	Peak of FFT of target's vibration
[80]	Yes	Yes	Yes	No	Yes	Yes	No	Peak of FFT of target's vibration
[91], [92]	Yes	Yes	Yes	No	Yes	Not necessary	No	Peak of FFT of target's vibration
[79]	No	No	Yes	No	Yes	No	No	Peak counting in the time domain
[88]	No	No	Yes	No	No	No	No	Peak of FFT of target's vibration
[49]	Yes	No	Yes	No	No	No	No	Peak of FFT of target's vibration

Fig. 8. Pulse oximeter used in [83].

from the Doppler-time map and used to develop a signal distortion compensation. This measure helps to remove the signal distortion that the driver's motions make while driving. In recent studies, the human body motion whether by simple filtering [49], [78] or a specific filter design [62], [80], [82], [91], [92], [94] cannot be removed reliably when the human body motion is within the breathing spectrum, which is less than 0.5 Hz [237]. In [238], the use of a camera system that comes with a microwave sensor has been investigated to develop a random body movement cancellation approach. The phase shift in the radar sensor was made up for using the random body motions that the camera captured.

The main cause of car body vibrations in a moving vehicle is the changes in the road surface. Depending on the type of vehicle, the power spectrum density (PSD) has a significant amount of content in the range between 1 and 100 Hz [239]. A mathematical framework was proposed in [91] and [92], whereby an accelerometer was attached to a RADAR-based sensor, allowing for the recording of acceleration. By reconstructing the movement of the seat and the passenger using these data, the corresponding Doppler was calculated. The signal received by radar was then denoised using the Doppler that resulted from the unwanted vibrational motion.

The clutter inside a vehicle reflects signals similar to a human, but it remains stationary over time. Therefore, clutter cancellation for UWB radars is crucial as these radars measure human body displacements based on the amplitude of signals. Strong clutter reflections can affect human body displacements in UWB signals. Clutters are typically suppressed using filtering techniques, such as motion filter [113], IIR moving average filter [82], [240], and pseudo-bi-dimensional EEMD [71].

Due to the confined space inside a vehicle, there are multipath signals. This issue is addressed rarely because most studies are focused on the vital sign monitoring of drivers. As radars can be installed close to the driver, the multipath effect is insignificant. Few studies on multiple target monitoring have mentioned this issue. In [90], the correlation coefficients between obtained vital signals in various locations are analyzed to choose the corresponding vital signs. In [241], the proposed method was able to distinguish the respiration signals of five participants seated close to one another using the DeepBreath subjects [90]. In this approach, each seat has a specific distance from the radar, which is different from other

TABLE IX

COMPARISON BETWEEN THE DIFFERENT IN-CABIN PUBLISHED PAPERS FOR VITAL SIGN MONITORING BASED ON FOUR IMPORTANT FACTORS, INCLUDING THE SELECTED VITAL SIGNS, ACCURACY OR ADVANTAGES, LIMITATIONS, AND THE NUMBER OF SUBJECTS

Reference	The vital sign	Accuracy or advantages	Limitations	No. of subjects
[62]	BR	• The maximum BR error: ±2 breaths • Proposing two applications, including occupancy detection, and BR estimation • In-cabin measurements and considering real situations like including a car seat for infants	• The accuracy of amplitude approach in UWB radars is dependent to range, since amplitude drops by range to the power of four based on the radar equation.	1
[78]	BR	• Maximum BR error: ±2 breaths • A deep investigation on sensor placement in 16 radar positions • Decent research on frequency selection based on reflected power from human skin • Two different signal processing approaches for online and offline analyses • Investigate the impact of the time window length on BR estimation	• Lack of real-time processing	1
[90]	BR and HR	• The HR error: 12.5%, Multiple targets. • Proposes a location-based Variational Mode Decomposition identify the vital sign of different subjects • Background removal by filtering	• Harmonic analysis might be applied to increase HR estimations.	2
[89]	BR and HR	• The BR and HR error: 7% and 5% respectively. • Multi-subject vital sign monitoring • Using w-band for automotive radars	• Lack of practical measures within the vehicle • The accuracy of amplitude approach in UWB radars is dependent to range, since amplitude drops by range to the power of four based on the radar equation. • Harmonic analysis might be applied to increase HR estimations.	2
[82]	BR and HR	• The maximum BR and HR error: ±1.2 breaths and ±2.5 beats. • Identifying the key factors that cause car crashes, such as distracted driving and mobile usage • Proposing an accurate fitting approach using R-square value	• Harmonic analysis might be applied to increase HR estimations.	1
[83]	BR	• The maximum BR error: ±1 breath • Accuracy of drowsiness detection: 87% • Comparing various machine learning classifiers	• Lack of collected data in real driving environments	1
[84]	BR and HR	• The accuracy of drowsiness: 71% • A significant amount of collected data	• Harmonic analysis might be applied to increase HR estimations. • Insufficient number of volunteers (5 subjects)	1

seats. Hence, the radar should not be placed on the line of symmetry of the car. Yang et al. [78] conducted extensive research on sensor placement to improve vital sign monitoring accuracy for a driver.

HR estimation by radar suffers from multiple challenges. The most important one is the higher harmonics of breathing vibrations. This issue becomes prevalent as this indicator interferes with the heartbeat signal. One solution to recognize HR from higher harmonics of breathing is harmonic analysis. It is based on the pulse train theory [232]. Estimating HR without harmonic analysis produces inaccurate and unreliable figures; this is because breathing harmonics can have stronger amplitudes than the HR peak in the frequency domain [232]. It has also been demonstrated that the heart vibrations in the frequency domain can be between two sequential harmonics of breathing vibration and have less amplitude. This creates

TABLE IX

(Continued.) COMPARISON BETWEEN THE DIFFERENT IN-CABIN PUBLISHED PAPERS FOR VITAL SIGN MONITORING BASED ON FOUR IMPORTANT FACTORS, INCLUDING THE SELECTED VITAL SIGNS, ACCURACY OR ADVANTAGES, LIMITATIONS, AND THE NUMBER OF SUBJECTS

Reference	The vital sign	Accuracy or advantages	Limitations	No. of subjects
[94]	BR	• The maximum BR error: ±2.96 breaths • Adaptive driver's movement compensation by a motion quantification index	• Lack of collected data in real driving environments • Lack of phase unwrapping in signal processing chain	1
[79]	BR and HR	• The maximum HR error: ±2 beats • A novel driver's motion compensation • Investigate the impact of the window length on HR variability • Examine the effects of many factors, such as the device locations, the pavement conditions, and the motion types	• Harmonic analysis might be applied to increase HR estimations.	1
[67]	HR	• The maximum HR error: ±4 beats • A comprehensive study of processing window size	• Harmonic analysis might be applied to increase HR estimations. • The HR is assumed to be 60 to 120. However, it could be more [49].	1
[88]	BR	• Anger prediction accuracy: 92.83% • Unique hardware design for online monitoring of driver • Collecting data from 100 people • PCA to feature selection	• Lack of diversity in collected data	1
[49]	BR	• Age classification accuracy: 96.25% • Collecting a valuable database	• Lack of phase unwrapping in signal processing chain • Lack of collected data in real driving environments	1

difficulty in HR estimation. Some studies have used simple filtering to remove breathing harmonics [49], [79], [80], [82], [84], [89], [90], [227], [242].

Some studies developed approaches to detecting abnormal breathing. In [237], the human vibration signal has been filtered up to 0.5 Hz, or 30 breaths per minute, to estimate the breathing signal. This indicates that the estimation technique only considers the primary peak. As a result, higher frequency information is omitted in the reconstructed breathing signal after filtering, and the breathing signal resulting from abnormal breathing with sharp peaks will be smoothed. Consequently, a level of conflated difficulty is added to the detection of this abnormal breathing.

The suppression of breathing vibrations, in service of garnering accurate HR estimation, has been studied extensively. Lin et al. [234] have employed EEMD and principal component analysis (PCA) to reduce the breathing vibration effect on heart vibrations. An iterative notch filter has also been utilized to suppress breathing harmonics [232], [243].

The fast Fourier transform (FFT) and continuous wavelet transform (CWT) are regarded as highly fundamental techniques for obtaining the BR [244], [245], [246], [247], [248], [249], [250], [252], [252]. With respect to the peak of the spectrum in a certain frequency band, these techniques can estimate the BR. For vital sign monitoring inside a vehicle, the most common estimation technique is the peak of the FFT of the target's vibration. The HR can also be estimated from its peak after taking FFT [231]. As discussed before, due to the presence of breathing harmonics close to the HR peak and other interferers, harmonic analysis is required for in-cabin applications [232]. Other estimation techniques, such as the maximum likelihood estimator (MLE), can be employed to estimate BR [253]. Cyclostationary is also a different method to improve the radar sensor's ability to detect vital signs [249], [254].

Table IX compares in-cabin published papers for vital sign monitoring under four important factors, including the selected vital signs, accuracy or advantages, limitations, and the number of subjects. The results of different papers demonstrated that up to two breaths' error was acceptable.

IV. CONCLUSION

In this article, the most recent advances in radar-based in-vehicle sensing technology were surveyed. It showed how radars could be used in occupancy detection, gesture recognition to assist drivers, and occupant status monitoring. We discuss the main approaches used in each application, explain how these approaches are used, and thoroughly examine the benefits and limitations. The most used main approach is BR and/or HR estimation, which is mostly employed for occupant status monitoring. Future works, particularly those involving millimeter-wave radars, will benefit from a high-level discussion of signal processing techniques, radar placement, and frequency selection in various applications. In terms of signal processing, phase unwrapping and harmonic analysis have been discussed as critical challenges in recent studies.

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