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An IoT Smart-Helmet Interlock with Alcohol Sensing, Vision-Based Helmet Verification and Accident Alerting

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Abstract

This paper reports a helmet-mounted safety system that conditions motorcycle ignition on two checks, that the helmet is worn and that the rider has not consumed alcohol, and raises a located alert if an accident is detected. The prototype couples infrared presence sensing and a metal-oxide alcohol sensor in the helmet to an Arduino controller, adds vision-based helmet verification on a Raspberry Pi Pico with camera, and uses an ESP8266 node with a satellite navigation receiver to publish status and location to a cloud dashboard, with a relay inhibiting the ignition. The interlock logic, sensor response law and alert-latency decomposition are formalised. The assessment is then explicit about three limitations that the source record does not address. The alcohol channel was never exposed to a certified reference, so its output remains an uncalibrated resistance ratio and no threshold in blood- or breath-alcohol terms can be justified; the paper therefore reports no concentration and no detection threshold. No stage of the alert path was time-stamped, so the end-to-end latency that determines whether the accident alert is useful is indeterminate and no response time is claimed. And no false-positive or false-negative rate was measured for either the infrared presence checks or the vision-based helmet check, which matters disproportionately here because a false positive strands a sober, helmeted rider. This revision adds the quantity a calibration would have to reach. The Indian legal limit of 30 mg of alcohol per 100 mL of blood corresponds, using the statutory blood and breath pair adopted in England and Wales as the conversion, to about 0.13 mg of ethanol per litre of breath; that is the concentration the interlock must resolve, and whether the fitted device spans it at useful resolution is not documented anywhere in the record. A further finding is that no accident-detection sensor appears in the component set at all, so the alerting function has no documented trigger. The safety, legal and tamper-resistance consequences of an ignition interlock are examined explicitly, and a measurement plan is specified.

Nomenclature

Symbol	Meaning
H, A	Helmet-worn and alcohol-detected indications (Boolean)
S	Ignition-enable output (Boolean)
R_s, R_0	Sensor resistance and clean-air baseline (Ω)

a, b	Device- and gas-specific constants of the response law
C	Ethanol concentration in the sampled air (mg/L)
C_{blood}, C_{breath}	Alcohol concentration in blood and in breath
r	Blood-to-breath conversion ratio adopted by a jurisdiction
τ	Firmware detection threshold (raw counts)
T_{e2e}	End-to-end alert latency (s)
t_1 to t_4	Stage latencies within the alert chain (s)
P_{fp}, P_{fn}	False-positive and false-negative probability
ϕ, λ	Latitude and longitude of the reported fix (degrees)

Introduction

Motorcycle casualties are dominated by two behavioural factors that are both detectable at the moment of starting a journey: riding without a helmet and riding after drinking. Because both are detectable before motion begins, they are amenable to an engineering control that conventional enforcement cannot provide, namely an interlock which simply declines to start the machine [1], [2].

A helmet is a convenient host for such an interlock. It is already worn on the head, so presence sensing is straightforward, and the rider's breath is close by, so an alcohol sensor placed inside the shell samples the relevant air. This paper reports a prototype of that kind, extended with vision-based confirmation that a helmet is genuinely present and with a cloud-published alert carrying the machine's location should an accident be detected.

The paper documents the design fully and is explicit about the boundary between what the prototype was observed to do and what would have to be measured before any of its safety claims could be relied upon.

1. Problem Statement

Smart-helmet prototypes are numerous and almost all report the same demonstration: the buzzer sounds, the relay opens, a message arrives. They very rarely report the quantities that decide whether such a device could be deployed, being the calibration of the alcohol channel, the false-positive rate of the presence checks, and the latency of the alert. An interlock that occasionally refuses to start a compliant rider's machine will be defeated by that rider within a week, so the false-positive rate is not a refinement but a precondition. That gap is the subject of this paper.

2. Objectives

The specific objectives of the work are as follows:

- To state the interlock logic formally and to identify the asymmetry it creates between the two error directions.
- To establish precisely why no alcohol concentration or threshold can be reported from this campaign, and what calibration would be required.
- To fix the concentration that a calibrated interlock would actually have to resolve, in the units the sensor works in.
- To decompose the accident-alert path into its stage latencies and to state which were recorded.
- To analyse the false-positive and tamper-resistance problems specific to interlocks, with the trials that would quantify them.
- To specify a measurement framework producing the three figures the design currently lacks.

3. Scope and Delimitation

The study covers the interlock logic, the sensing relations, the prototype as documented, and the specification of the measurements that were absent. It excludes any claim of alcohol concentration, detection threshold in blood- or breath-alcohol terms, detection accuracy, false-positive or false-negative rate, alert latency or localisation accuracy, because none was measured. It also excludes any claim of legal suitability for an ignition interlock, and any claim about accident detection, since no accident-detection sensor is documented in the component set.

4. Contributions

1. A formal statement of the interlock logic and of the sensor response law that any threshold must be derived from.
2. A precise account of why no alcohol concentration or threshold can be reported from this campaign, and what calibration would be required.
3. A statement, new to this revision, of the breath-alcohol concentration corresponding to the applicable legal limit, which is the quantity a calibrated interlock must resolve.
4. A decomposition of the accident-alert path into four stage latencies, none of which was recorded, together with the

observation that no accident-detection sensor appears in the component set.

5. An analysis of the false-positive and tamper-resistance problems specific to interlocks, with the trials that would quantify them.

The remainder of the paper is organised as follows. Section II reviews related work and fixes the applicable limits. Section III gives the governing relations. Section IV describes the prototype. Section V reports the results and their honest reading. Section VI treats the safety, legal and tamper questions, and Section VII the limitations. Section VIII gives the measurement framework, and Sections IX and X the conclusion and the future scope.

Related Work

The protective effect of helmets is among the best-established findings in injury epidemiology, and systematic reviews of helmet use consistently associate wearing with substantial reductions in head-injury severity [1]. Alcohol ignition interlocks have a parallel evidence base in the automotive domain, where programme evaluations report reduced recidivism while the device remains fitted [2]; that literature also documents the circumvention behaviours which any interlock design must anticipate.

On sensing, Wang and colleagues [3] review metal-oxide gas sensors and document the two properties that govern the present design: a power-law resistance response to target-gas concentration, and a marked sensitivity of both baseline and slope to humidity and temperature. Because breath is warm and near-saturated, this is not a marginal correction for a sensor placed inside a helmet. For the vision stage, helmet detection from images is a well-studied classification problem, with reported accuracy strongly dependent on illumination, viewpoint and the training distribution [4]. For localisation and alerting, Kaplan and Hegarty [5] give the standard treatment of satellite-navigation error and initialisation behaviour. The Arduino, Raspberry Pi Pico and ESP8266 platforms supply the compute layers [6], [7], [8].

Table 1. Representative Related Work and its Relation to This Study

Ref.	Year	Focus and scope	Method and validation	Relation to this work
[1]	—	Helmet use and head injury	Systematic reviews	Motivates the wear check
[2]	—	Alcohol ignition interlocks	Programme evaluations	Interlock precedent and circumvention
[3]	2010	Metal-oxide gas sensing	Review of response and artefact	Sensor law and humidity caution
[4]	—	Vision-based helmet detection	Image classification studies	Basis and limits of the camera check
[5]	2017	GNSS principles and error	Reference text	Fix quality for the alert
[6]	—	Arduino and ATmega328P	Vendor documentation	Interlock controller
[7]	—	Raspberry Pi Pico	Vendor documentation	Vision-stage controller
[8]	—	ESP8266 platform	Vendor documentation	Uplink and dashboard
[9]	1988	Motor Vehicles Act, Section 185	Statute	The limit a threshold must be referenced to

Three entries in this table point to bodies of literature rather than to single papers, which the source record left entirely unspecified. They are marked as such here rather than presented as definite citations; a future revision should name the specific systematic review, the specific programme evaluation and the specific helmet-detection study on which each claim rests.

1. The Concentration an Interlock Must Resolve

A detection threshold is meaningful only against a legal or physiological limit. In India, the applicable limit is 30 mg of alcohol per 100 mL of blood, equivalently a blood alcohol concentration of 0.03 %, set under Section 185 of the Motor Vehicles Act, 1988 [9]. That is one of the stricter limits internationally: Scotland and much of Europe use 50 mg per 100 mL, and England and Wales 80 mg per 100 mL.

A breath sensor does not measure blood, so the limit must be converted. Jurisdictions adopt a statutory blood-to-breath ratio for this purpose, and England and Wales fix the pair explicitly, prescribing 80 mg per 100 mL in blood alongside 35 micrograms per 100 mL in breath, which corresponds to a ratio of about 2,290 to 1.

Applying that ratio through Eq. (5) gives the values in Table 2 and Fig. 1.

Table 2. Legal Limits Expressed in the Units a Breath Sensor Works In

Jurisdiction	Blood limit	Equivalent breath concentration	Basis
India	30 mg/100 mL (0.03 %)	about 0.13 mg/L	Statute [9]; conversion computed
Scotland and much of Europe	50 mg/100 mL	about 0.22 mg/L	Published limit; conversion computed
England and Wales	80 mg/100 mL (0.08 %)	0.35 mg/L (statutory)	Statutory blood and breath pair

The England and Wales figures are the statutory pair and are used here as the conversion anchor; the other breath figures are computed from the blood limits by Eq. (5) using that same ratio. The blood-to-breath ratio is a legal convention that varies between jurisdictions and between individuals, so these conversions indicate the order of magnitude a sensor must resolve rather than a legally binding equivalence. Nothing in this table was measured on the prototype.

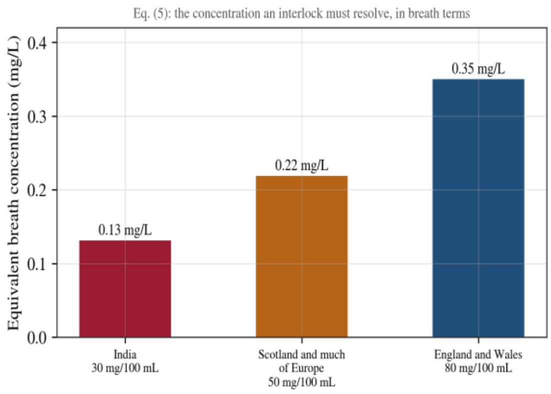

Figure 1: Legal blood-alcohol limits expressed as equivalent breath concentrations by Eq. (5). The Indian limit is the leftmost and the lowest.

The consequence is specific. An interlock intended to enforce the Indian limit must resolve a change in the sampled air at roughly 0.13 mg per litre, and must do so reliably enough that a rider just below the limit is not stranded and a rider just above it is not enabled. The detection range and resolution of the fitted device are not recorded anywhere in the project material, so it cannot be established from this record whether the sensor spans that concentration at useful resolution. That is a separate deficiency from the absence of calibration, and it would remain even after a calibration was attempted.

System Modelling

1. Interlock Logic

The ignition-enable output is the conjunction of a positive helmet indication and the absence of an alcohol indication,

$$S = H \wedge \neg A \qquad (1)$$

so the machine starts only in the single state where both conditions are satisfied. The asymmetry of Eq. (1) is important and is set out in Fig. 2: three of four states inhibit starting, so any sensing error that produces a spurious negative helmet indication or a spurious alcohol indication strands a compliant rider.

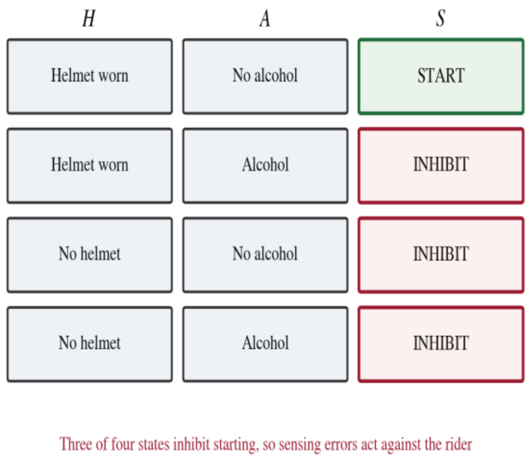

Figure 2: Interlock states from Eq. (1). Only one of four states permits starting, so sensing errors overwhelmingly act against the rider.

2. Alcohol Sensor Response

A metal-oxide element does not report concentration. It reports a resistance whose ratio to its clean-air baseline follows approximately

$$\frac{R_s}{R_0} = aC^{-b} \qquad (2)$$

with a and b specific to the target gas and the individual device, and with the baseline drifting under humidity and temperature [3]. A firmware threshold applied to the raw analogue count is therefore a threshold on the resistance ratio, not on breath-alcohol concentration, unless Eq. (2) has been inverted using calibration against a known mixture. Fig. 3 shows the family of curves the coefficients select between; none was determined for this device.

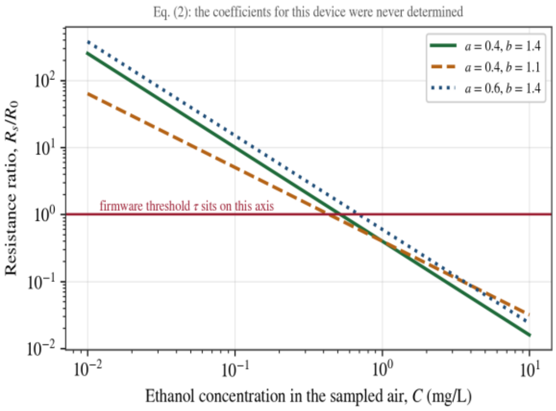

Figure 3: Illustrative metal-oxide response law of Eq. (2). The firmware threshold sits on the vertical axis, not on the concentration axis.

3. Converting a Legal Limit to a Sensed Quantity

Because the sensor samples breath while the limit is written in blood, the two are related by the jurisdiction's adopted ratio,

$$C_{breath} = \frac{C_{blood}}{r} \quad (5)$$

Equation (5) is what turns a statutory number into a target for calibration, and it is evaluated in Section II-A. Without it, a threshold expressed in raw counts cannot be connected to any legal standard at all.

4. Detection Errors

For either check of presence, performance is the pair

$$P_{fp} = \Pr\{\text{inhibit} \mid \text{compliant}\}, \quad P_{fn} = \Pr\{\text{enable} \mid \text{non-compliant}\} \quad (3)$$

and both require labelled trials to estimate. For an interlock the two errors have very different consequences: a false negative defeats the safety purpose, while a false positive destroys user acceptance and invites circumvention.

5. Alert Latency

The accident-alert path decomposes into detection, uplink, cloud relay and delivery,

$$T_{e2e} = t_1 + t_2 + t_3 + t_4 \quad (4)$$

and the value of a located alert falls sharply as this latency rises. Evaluating Eq. (4) requires a time stamp at each node of Fig. 4; none was recorded.

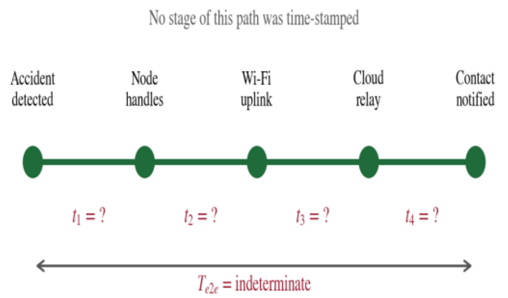

Figure 4: Accident-alert path of Eq. (4). Every stage latency is unmeasured.

Prototype

A. Architecture

Fig. 5 shows the system. Inside the helmet, an infrared sensor detects head presence and an MQ-3 alcohol sensor samples the rider's breath; both feed an Arduino controller which drives a buzzer and the ignition relay and writes status to a 16 by 2 display. A Raspberry Pi Pico with camera performs image-based helmet verification independently of the infrared check. An ESP8266 node with a satellite-navigation receiver publishes status and position to a cloud dashboard. The two items shown as absent at the foot of the figure are the ones on which Sections V-C and V-E turn.

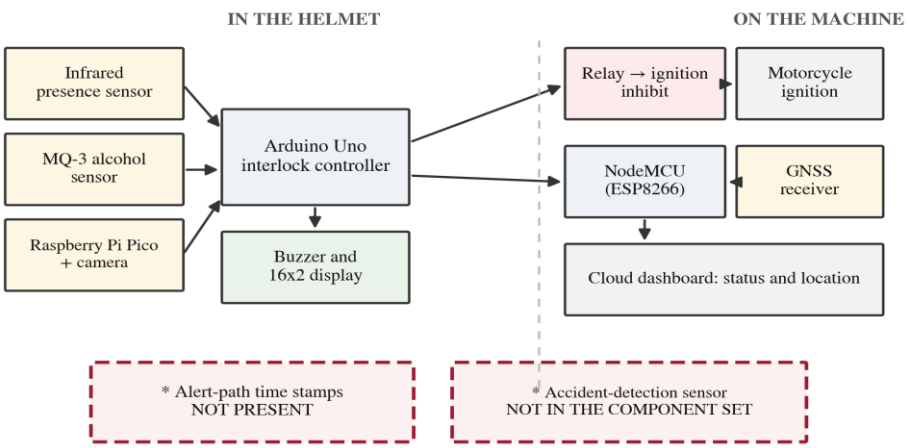

Figure 5: Prototype architecture. Two independent helmet checks feed one interlock; no timing instrumentation was placed on the alert path and no accident-detection sensor appears in the component set.

2. Apparatus

Table 3 lists the prototype as documented.

Table 3. Prototype as Documented

Item	Type / rating	Quantity
Interlock controller	Arduino Uno (ATmega328P)	1
Vision controller	Raspberry Pi Pico	1
Camera	Raspberry Pi camera	1
Presence sensor	Infrared	1
Alcohol sensor	MQ-3, metal-oxide; detection range not stated	1
Wi-Fi node	NodeMCU (ESP8266)	1
Navigation receiver	GNSS, serial NMEA	1
Relay module	Ignition inhibit	1
Buzzer and display	Audible alert, 16 by 2 character	1 each
Power supply	Regulated 5 V	1

No impact, tilt, accelerometer or other accident-detection sensor appears in this list, which is the basis of the observation in Section V-E. The alcohol sensor's stated detection range is also absent, which is the basis of the observation in Section II-A.

3. Procedure

- Mount the infrared and alcohol sensors inside the shell; wire the controller, relay, buzzer and display.
- Program the interlock according to Eq. (1) and the vision stage on the Pico.
- Bring the Wi-Fi node online and confirm the dashboard receives status.
- Exercise each condition, helmet absent and alcohol present, and observe the relay and buzzer response.

Results

1. What the Campaign Established

The system was built and its logic exercised: with the helmet absent the ignition remained inhibited, and presenting an alcohol source to the MQ-3 sensor activated the buzzer and held the relay open. Sensor status was visible on the cloud dashboard. Those behaviours were observed and are reported without extension.

2. Why No Alcohol Threshold Is Reported

The alcohol channel was never exposed to a certified reference gas or compared against a calibrated breathalyser. Three consequences follow. The firmware threshold is a raw analogue count, so it corresponds to no stated breath- or blood-alcohol concentration and cannot be related to the limit of Table II. Equation (2) was never inverted, so the coefficients for this device are unknown. And because breath is warm and near-saturated while the baseline is humidity-dependent [3], the baseline in use during a real breath sample differs from the baseline in ambient air, in a direction and magnitude that were not characterised. This paper therefore reports no concentration, no threshold and no detection accuracy for the alcohol channel.

It is worth being precise about what the demonstration did show. Presenting an alcohol source produced a response, which establishes that the channel is alive and responds to ethanol in some quantity. It does not establish that the response distinguishes a rider at 0.02 % blood alcohol from one at 0.04 %, which is the discrimination the Indian limit actually requires and which lies within a factor of two on either side of a single threshold.

3. Why No Response Time Is Reported

The alert path was exercised but not timed: no time stamp exists at detection, uplink, cloud relay or delivery, so none of the stage latencies in Eq. (4) is known and the end-to-end figure is indeterminate. For an accident alert this is the primary performance figure, and no value is asserted here.

4. The Two Helmet Checks Were Never Scored

The design carries two independent helmet checks, being infrared presence and camera-based classification, but neither was evaluated over repeated trials, so the error probabilities in Eq. (3) are unknown for both. Two structural cautions can nonetheless be stated without measurement. An infrared presence sensor inside a shell responds to any nearby reflective surface, so it verifies that something occupies the shell rather than that a head does; and vision-based helmet classification is reported to degrade with illumination, viewpoint and distributional shift [4], which is precisely the variation a road environment supplies. The vision check is a sound instinct as a partial answer to the first problem, but it substitutes one unmeasured error rate for another.

The record also does not state how the two checks are combined. A conjunction of two independent checks multiplies the false-negative resistance but adds their false-positive rates, which under the asymmetry of Eq. (1) is the direction that harms acceptance. A disjunction does the reverse. Which was implemented is not documented, and it materially changes the device's behaviour.

5. The Accident-Detection Trigger Is Absent

A further gap should be stated plainly because it is structural rather than a matter of missing instrumentation. The system publishes a located alert if an accident is detected, but no accident-detection sensor appears anywhere in the component set of Table III: there is no accelerometer, no tilt switch, no impact sensor and no documented threshold on any existing channel. The alerting path therefore has no documented trigger, and the accident-detection function is design intent rather than a realised block. Either such a sensor must be added with its threshold stated, or the paper's own description should say that alerting is manual.

6. What the Campaign Supports

Table 6 states the position quantity by quantity.

Table 6. Demonstrated, Unmeasured and Indeterminate Quantities

Quantity or capability	Value	Status
Interlock inhibits ignition	yes	demonstrated
Alcohol source triggers alarm	yes	demonstrated
Dashboard receives status	yes	demonstrated
Alcohol concentration	—	indeterminate; no calibration
Detection threshold in blood-alcohol terms	—	indeterminate
Alcohol sensor detection range	—	not documented
False-positive and false-negative rate, infrared check	—	not measured
False-positive and false-negative rate, vision check	—	not measured
How the two checks are combined	—	not documented
Alert latency T_{e2e}	—	indeterminate; no time stamps
Localisation accuracy	—	not measured
Accident-detection sensor	—	not in the component set
Fail-secure or fail-open behaviour	—	not specified or tested
Tamper resistance	—	not tested
Breath concentration at the Indian limit	about 0.13 mg/L	computed, Eq. (5), from [9]

Safety, Legal and Tamper Considerations

An ignition interlock is not an ordinary output stage, because it withholds a function the user expects. Three consequences follow directly from the architecture and are stated rather than deferred.

False positives are the acceptance problem. Under Eq. (1) three of four states inhibit starting, so every unmeasured error rate in Section V-D acts predominantly against a compliant rider. A device that strands a sober, helmeted rider in a car park at night will be bypassed, and a bypassed interlock provides no protection at all. This is why the false-positive rate is a precondition for deployment rather than a performance refinement.

Circumvention is documented in the interlock literature. Breath samples can be provided by another person and presence sensors satisfied by an object; the automotive interlock literature records both [2]. The vision check is a partial answer to the second, which is a sound design instinct, but its own error rates are unmeasured.

Legal status. Whether a privately fitted device may inhibit a vehicle's ignition, and whether alcohol readings from an uncalibrated sensor carry any standing, are jurisdiction-dependent questions. Section 185 of the Motor Vehicles Act, 1988 provides for breath testing by an authorised officer using a breath analyser [9]; nothing in that framework confers standing on a privately fitted uncalibrated sensor. No claim of legal suitability is made here.

Limitations

The following limitations bound every claim made in this paper.

- The alcohol channel was never calibrated against a certified reference, so its threshold corresponds to a raw resistance ratio and no concentration, threshold or accuracy is reported.

- The fitted sensor's detection range and resolution are undocumented, so it cannot be established that the device spans the concentration of Table II even in principle.
- The breath-equivalent figures in Table II are computed from statutory blood limits using the England and Wales statutory ratio. The blood-to-breath ratio is a legal convention that varies between jurisdictions and individuals, so these indicate an order of magnitude rather than a binding equivalence.
- Neither helmet check was scored over repeated trials, so both error probabilities are unknown, and the record does not state how the two checks are combined.
- No stage of the alert path was time-stamped, so the end-to-end latency is indeterminate for this build, not merely uncertain.
- No accident-detection sensor appears in the component set, so the alerting function has no documented trigger and no threshold to evaluate.
- The failure mode on sensor fault or power loss was neither specified nor tested, so it is unknown whether the device fails secure or fails open.
- No tamper trial was conducted, so resistance to the circumvention routes documented in the interlock literature is unknown.
- Figures 2 and 3 illustrate the governing relations. They contain no data point from this hardware.
- No claim of legal suitability for an ignition interlock is made anywhere in this paper.

Proposed Measurement Framework

Fig. 6 shows the evaluation the design requires: calibrate the sensing, score the checks, then time the alert. The three branches are independent and each produces one of the figures the design currently lacks.

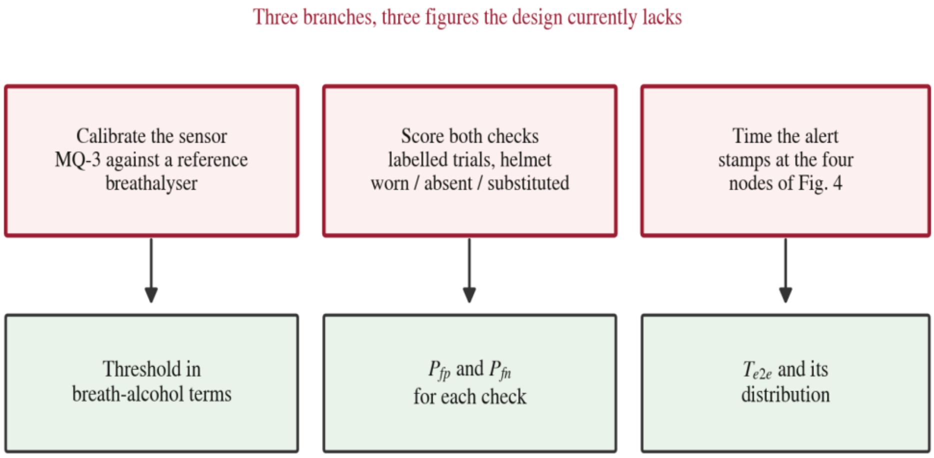

Figure 6: Measurement framework. Each branch produces one of the three figures the design currently lacks.

1. Measurement Plan

Table 5 sets out the measurements required, and Table 6 gives the context values that are statutory, literature or computed rather than results of this work.

Table 5. Measurement Plan Required Before Any Safety Claim

Measurement	Method	What it yields
Confirm the sensor range	Datasheet capture for the fitted device	Whether it spans the concentration of Table II
Calibrate the alcohol channel	Comparison against a calibrated breathalyser across concentrations and humidities	Coefficients of Eq. (2); a threshold in breath-alcohol terms
Characterise the humid baseline	Baseline in ambient air against baseline during a real breath sample	The drift the threshold must tolerate
Score the infrared check	Labelled trials: helmet worn, absent, object substituted	P_{fp} and P_{fn} by Eq. (3)

Score the vision check	The same trials across lighting and viewpoint conditions	P_{fp} and P_{fn} by Eq. (3), separately
Document the combination rule	Firmware inspection and a joint trial	The device's actual error behaviour
Time the alert path	Time stamps at the four nodes of Fig. 4	T_{e2e} and its distribution
Specify accident detection	Add an impact or tilt sensor with a stated threshold, or state that alerting is manual	A documented trigger for the alert
Define and test the failure mode	Deliberate sensor fault and power interruption	Fail-secure or fail-open behaviour
Conduct tamper trials	The documented circumvention routes, including substituted breath and objects in the shell	Resistance to the known defeat methods

Table 6. Illustrative and Statutory Figures (Not Results of This Work)

Item	Value	Status
Indian legal blood-alcohol limit	30 mg/100 mL (0.03 %)	statute [9]
Equivalent breath concentration	about 0.13 mg/L	computed, Eq. (5)
Consumer GNSS accuracy	Metres to tens of metres	literature [5]
MQ-3 humidity sensitivity	Largest at high relative humidity	literature [3]
Measured breath-alcohol threshold	—	indeterminate
Measured alert latency	—	indeterminate
Measured false-positive rate	—	indeterminate

Statutory and literature entries are quoted for orientation only and were not measured on this prototype.

Conclusion

A helmet-mounted safety system conditioning motorcycle ignition on helmet use and sobriety, with vision-based confirmation and a cloud-published located alert, was designed and built. The interlock logic operated as intended in demonstration: the ignition relay remained open with the helmet absent or an alcohol source present, and status reached the dashboard.

Beyond that demonstration the campaign supports no quantitative claim. The alcohol sensor was never calibrated against a reference, so its firmware threshold corresponds to a raw resistance ratio rather than any breath-alcohol concentration and no threshold or accuracy is reported. This revision fixed the target such a calibration would have to reach: the Indian limit of 30 mg per 100 mL of blood corresponds to roughly 0.13 mg of ethanol per litre of breath, and the fitted device's detection range is not documented, so it cannot be established that the sensor spans that concentration at useful resolution.

Neither the infrared nor the vision helmet check was scored over repeated trials, so their false-positive and false-negative rates are unknown, and the rule combining them is undocumented. This gap matters more than usual, because Eq. (1) inhibits starting in three of its four states, so a spurious inhibit strands a compliant rider and invites circumvention. No stage of the alert path was time-stamped, so the end-to-end latency is indeterminate; and the accident-detection mechanism itself is absent from the component set, so the alerting function has no documented trigger at all.

The safety, legal and tamper-resistance consequences specific to interlocks were examined, and a three-branch measurement framework was specified, being calibrate the sensor, score the checks and time the alert, which would convert a working demonstration into a device whose safety claims could be relied upon.

Future Work

Several extensions follow directly from the limitations above.

- Confirm the sensor range, then calibrate-Record the fitted device's detection range and check it against Table II before calibrating; then compare the output against a calibrated breathalyser across concentrations and humidities so that Eq. (2) can be inverted and a threshold stated in breath-alcohol terms.
- Score both helmet checks-Run labelled trials, being helmet worn, helmet absent

and object substituted, across lighting conditions to estimate Eq. (3) for the infrared and vision checks separately, and document how they are combined.

- Time the alert path-Instrument the four nodes of Fig. 4 so that the end-to-end latency and its distribution become results.
- Specify accident detection-Add and document an impact or tilt sensor with a stated threshold, or state that alerting is manual.
- Define and test the failure mode-Decide fail-secure or fail-open, implement it explicitly, and test sensor-failure and power-loss cases.
- Conduct tamper trials-Test the documented circumvention routes, including substituted breath and objects placed in the shell.

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