Head Up Displays symbology (HUD) :
Pre normative study for DGAC/SFACT.

Final report (phase I).

Authors : P. Le Blaye – ONERA/DCSD (+ English translation)
C. Roumes, M.-P. Fornette, C. Valot – IMASSA

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Abstract :

This report is the final report of the first phase of a study of head up displays (HUD) symbology conducted for DGAC/SFACT, in the frame of its pre normative research program for civil aviation safety.

This report describes the main steps and results of the study :

1. Comparative analysis of the JAA and FAA regulations concerning HUD in general, and more especially, the specifications about their symbology.
2. State of the interpretation of the existing regulations, through the interviews of certification experts.
3. Comparative analysis of the symbologies of existing HUD products and comparison with the requirements of the regulation ;
4. Current state of the operational use of HUD, through the available safety reporting systems and interviews with the users ;
5. Synthesis of the lacks of the regulation in regard with the needs of the certification experts and with the operational difficulties encountered by the users.

Key words :

civil aviation – human factors – regulation - symbology – head up display – HUD

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1. Introduction

1.1. Subject of this report

This document constitutes the final report of the first section of the pre-normative study on the symbologies of head-up displays (HUD), carried out on behalf of the SFACT in response to the invitation to tender n°98/01, emitted within the framework of the functional program for pre normative research on the safety of civil aviation [ref. 1, Appendix 1]. This study is laid down over one duration maximum 2 years, the first year being notified 03 July 2000 [ref. 2].

The study is carried out under the responsibility of the System Control and Flight Dynamics Department (DCSD) of ONERA in collaboration with the Military Institute of Aerospace Medicine (IMASSA) and the Flight Test Centre (CEV), and with the participation of airline operators using HUD (Air France, Brit' Air, L'Aeropostale).

1.2. The issues behind this study

Contrary to FAA regulation, JAA documents concerning HUD (references JAA HUDS 901, 902, 903) do not give precise directives on the symbols which it is necessary to see appearing in a HUD and these documents were the subjects of divergent interpretation between the JAA and FAA certification teams. The aim of the study is to make recommendations for an evolution of the JAA regulation on the HUD symbologies and in particular on the symbols which must necessarily appear or not in a HUD. These recommendations must be done on rigorous experimental bases, integrating Human Factors.

1.3. The field of the study : the existing HUD

In order to limit the field of this study and in agreement with the experts of DGAC, the study brought back here relates primarily to the HUDs such as they exist today in civil transport aviation. One will thus indicate under the generic term HUD, an flight instrument presenting head-up information in superposition to the external vision, in the form of numerical (alpha numerical characters) or analogue (geometrical form in a two dimensions space). Such a HUD shows the following fundamental characteristics: collimated ad infinity, conformity with the external world, monochrome (for further discussion, see these terms in the glossary in Appendix 4). It is intended for use in civil transport aviation, mainly in the current context of use (en–route flight and controlled airspace with existing navigation aids).

The study does not relate directly to possible future uses of the HUD, in particular for the presentation of information elaborating from digital terrain data bases (SVS) or from sensors imagery (EVS), even if the issues specific to the HUD of today will be without any doubt relevant, if not exacerbated, with the addition of these new sources of information.

Also, the problems strongly linked with the possible future evolutions in the operation of the system of air transport are not tackled precisely. Thus, the complementarity of the HUD with the TCAS or the presentation of information in a free-flight context largely exceed the object of the study.

1.4. The methodology of the study

The methodology adopted for this first phase of the study comprises the following stages:
1. Comparative analysis of the JAA and FAA regulations
2. Analysis of the interpretation of the regulations, through discussions with the certifiers
3. Comparative analysis of the symbologies of existing HUD and confrontation with the regulation
4. State of the operational use of the HUD, through sources of experience feedback and interviews with the users

5. Synthesis of the lacks in the regulation compared to the needs for certification and identified operational difficulties.

2. History and technique: different practices, different symbologies with various concepts of use

2.1. Precursors

Historically, the HUD appeared in the years 1950 on military aircraft as sights for gun firing, and not as flight instruments. For this application, the HUD had significant advantages on its fixed mechanical predecessors: presentation of information brought up to date according to the shooting conditions, position in conformity with the external world and benefits of flying head up to follow the target.

The first developments of HUD as a piloting instrument took place in Great Britain. The English approach consists in primarily presenting a horizon and a symbol of reference plane, as well as the values of speed and altitude, with the rough guidance information provided by the flight director of the plane.

The symbols are then not necessarily conformal to the external world: in particular, much work and discussions concerned the need for adopting conformal pitch scales, as the compressed scales can contribute to improve the control of pitch attitude, in particular when this one is high.

The years 1960 see the development and the validation of elements of symbologies which are found on the majority of the HUD of today. Thus, Gilbert Klopfstein, test engineer at the CEV then at Thomson-CSF, proposed a coherent symbology which as well as possible exploits the specific capacities of head up displays (conformity and intuitive analogue symbols) and the angular relations between the piloting parameters (attitude, angle of attack, potential flight path). It presents a Flight Path Vector, which facilitates the pilot’s task by allowing direct perception of the angle of attack and of the potential flight path, as well as a graduated horizon and a synthetic runway with positioning information on the ILS (Figure 1). This symbology allows an intuitive and precise piloting approaches with or without visibility. The level of clutter is minimum; the absence of the values of altitude, course and speed should be noticed. This symbology inspired the PERSEPOLIS experimental symbology in particular, then the symbologies of the planes by Dassault (Mirage and Falcon families).

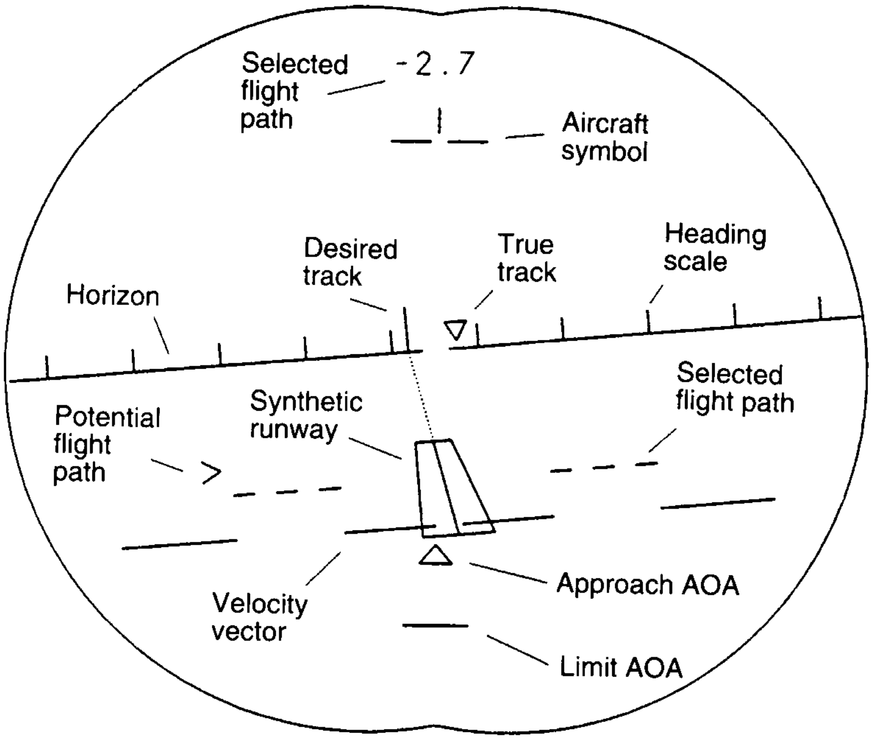


Figure 1 : the Klopfstein symbology (1966).

At the same time, American understands the potential interest of the association of a flight director in conformity with the Flight Path Vector, for piloting precision approaches. These elements can be associated with a synthetic representation of the ILS beam in order to help control the trajectory. These symbology elements are established gradually on the HUD of American fighters. Thus, the symbology of the A-7D presents this information, of which an inertial Flight Path Vector, as well as information of piloting in the form of scales, with a provision in T basic (Figure 2). Today, the American military HUD use a similar symbology, supplemented with alphanumeric information.

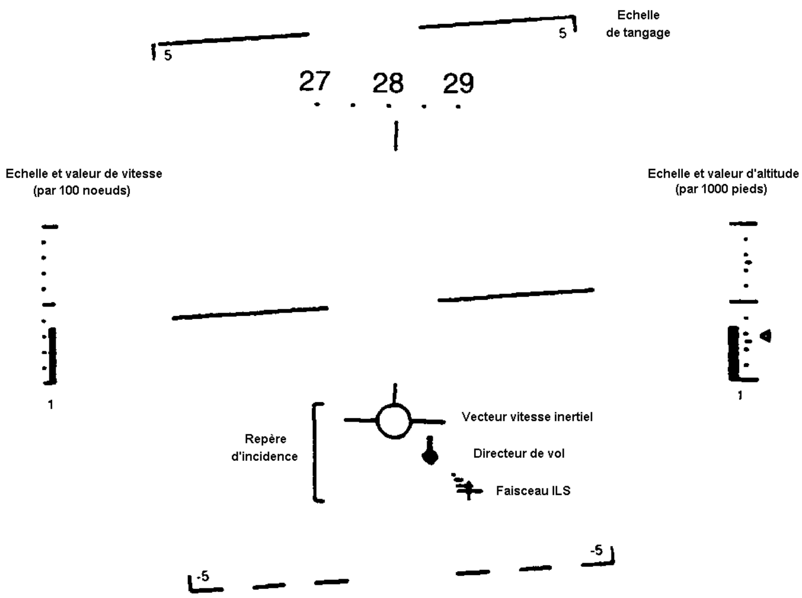


Figure 2 : The A-7D symbology in its landing mode.

2.2. The development of the HUD in civil aviation

The introduction of the HUD into the civil cockpits is justified mainly as an assistance for approach.

Indeed, the traditional methods of approach pose various types of specific problems, depending on the conditions of visibility met.

Thus, in **visual approach**, the perception of height and trajectory in particular in the vertical plane can be dangerously affected by the conditions of wind and luminosity or by parameters such as dimensions or slope of the runway. The head up presentation of information of trajectory (inertial Flight Path Vector, runway symbol, course and slope desired) in conformity with the external vision then improves considerably the precision of the approach, while piloting information (angle of attack, speed and potential flight path) facilitates work with the controls by removing the iterations necessary in traditional piloting. The recent HUD propose a mode of symbology dedicated to the visual approaches, which essentially takes again the analogue elements of the Klopfstein symbology, but inertial Flight Path Vector instead of the aerodynamic Flight Path Vector.

During **instruments approach**, the transition from head-down traditional instruments to head-up flight at the time of the visual acquisition is a delicate phase, in particular when it is close to the flare manoeuvre. The presentation of head up information, with the addition of ILS guidance symbology, constitutes a first possible solution for the approaches by bad visibility in manual piloting. Thus, the use of the HUD makes it possible indeed to remove the delicate transition at visual acquisition during instruments approaches.
An alternative to manual piloting, for the planes capable of automatic landing, is to use the HUD like a means of monitoring the autopilot. It is then enough to present control information, such as the rough deviations from the ILS beam and their allowed maximum values. So, the HUD may be used in manual piloting only in the rare case of failure of the automatic landing below the decision height. This concept called hybrid is proposed initially per Sextant on Mercure aircraft then on Airbus 320, and more recently, on Boeing 737 of L'AEROPOSTALE and MD82 of Alitalia (Figure 3).

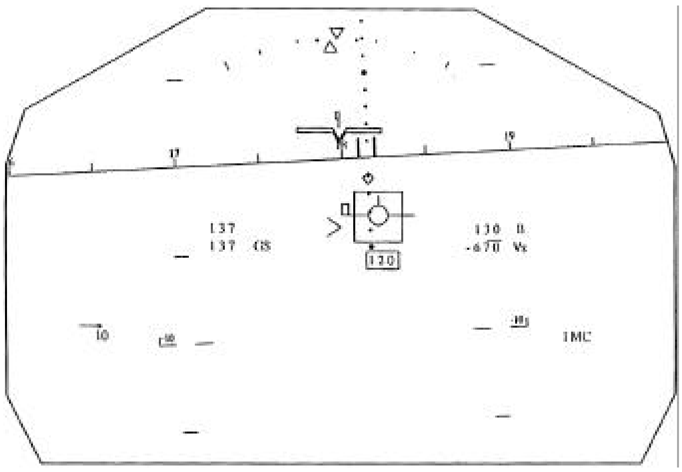


Figure 3 : The Sextant HFDS symbology for MD82.

2.3. The differentiation between concepts of use

For low visibility approaches, one thus sees appearing three principal concepts of employment, to which correspond as many tendencies in the constitution of HUD symbologies:

- The **'manual' concept**, of rather Anglo-Saxon origin, is based on a copy of the head down instruments on the HUD with the presentation of guidance information; the HUD is regarded as a primary flight instrument. This concept is generally applied in the objective to improve the operational and thus commercial capacities. Indeed, the addition of a HUD can allow certification for category IIIa approaches in manual piloting of a plane only certified for category II without the HUD, at a cost quite lower than that which would represent the development of the additional chain necessary for automatic approaches. In particular, the products of Dynamics Flight are at the origin of the development of the HUD in the civil aviation, with, initially, the installation of HUD for the retrofit of old planes (B 727, B 737, MD 83), and currently on new planes (CRJ, and Falcon certified up to category III – DH above 50 ft - with a HUD).

- The **'monitoring' concept**, intended for the planes capable of approaches under autopilot, rather recommends the presentation in an intuitive and uncluttered form of rough piloting information. The HUD being regarded as a specific instrument which facilitates piloting into VMC and the monitoring of the automatism into IMC, guidance information is not considered to be necessary. In this concept, the use of the HUD becomes optional, delivered to the preference of the crew (case of Airbus 320).
- The **'hybrid' concept**, of French origin, can be described as an extension of the monitoring concept in order to allow an improvement of operational capacity. This concept is justified economically for example on a basic plane authorised for category IIIa approaches in order to carry out category IIIb approaches automatically with HUD monitoring, in particular under difficult operating conditions such as met in North of Italy by Alitalia or by Alaska Airlines in Canada. The HUD thus allows an "operational credit" (case of L'AEROPOSTALE B-737, Alitalia MD 82 or, historically, Airbus 320 before the extension of its certification for the category IIIb automatic approaches without the assistance of the HUD). In this concept, guidance information are also not necessary: Indeed, it is estimated that the continuation of the landing in manual piloting under the DH does not require the presence of guidance information. This phase lasting approximately 3 seconds for a category IIIb approach, the presentation of rough information and of the reference glide slope is enough to pilot the plane until the landing. It should be noted that the use of the hybrid HUD under the extreme conditions of its certification is mandatory.

These various concepts naturally find their correspondence in the regulation.

Indeed, this one distinguishes two types of systems according to the level of safety offered in the event of a failure (see for example FAA AC 120-28D):

- a "fail passive " system is a system which in the event of a failure does not cause a significant deviation of the trajectory or attitude of the plane;
- a "fail operational system" is a system which makes it possible to conclude the phase of flight following a failure of the one of its components occurring after the passage of a point specified during the analysis of security (for example, the alarm height).

It is thus possible to conceive 3 types of all-weather landing system architectures, such as described under part E of the JAR-OPS 1 (see the glossary) :

<u>1) Fail passive systems</u>

This safety level is necessary to perform automatic category IIIa approaches.

Under normal operation, 2 autopilots (AP) function in parallel. If a deviation is detected between the 2 AP, the 2 pieces of equipment are declared out of use and the pilot takes the controls. At the time of the failure, the maintenance of the trajectory is guaranteed (no deviation of trajectory) but manual recovering must be carried out. The category IIIa minima are such as the pilot can finish the approach manually if a failure appears at the DH.

The addition of a HUD of manual, self-monitored concept and introducing an autonomous flight director, can also provide the same level of safety.

<u>2) Fail-operational systems</u>

This level of safety is necessary for automatic category IIIb approaches. Under normal operation, 3 AP are working in parallel. The redundancy makes it possible to always have an operational AP which guarantees an automatic approach until touch down. The category IIIb minima are such that the pilot cannot finish the approach manually if a failure appears at DH; this is why the automatic approach is guaranteed until touch down. In this context, the HUD belongs to the monitoring concept, its use is optional.

3) Fail-operational hybrid systems
This architecture is an alternative to the preceding one to increase the operational capability from category IIIa to category IIIb. Under normal operation, 2 AP function in parallel and a HUD is used for monitoring the automatic approach. If a deviation is detected between the 2 AP, the 2 pieces of equipment are declared failed and the pilot manually finishes the approach with the HUD. At the time of the failure, the maintenance of the trajectory is guaranteed (no significant deviation from the trajectory) but a transition to manual control must be carried out. It is considered that the monitoring by the pilot using the HUD during all the approach enables him to finish manually: this is the hybrid concept.

In order to avoid an over simplification, it should be noted that the most recent HUD offer multiple modes in order to be able to be used in all the phases of flight whatever the conditions of visibility. They can be used as well as flight instrument or as monitoring instrument, within the limits of their certification, which contributes to scramble the relation between the concept of employment and the symbology. The commercial will to extend the field of use of the HUD tends to increase the diversity of the symbols presented ; fortunately, this tendency is partly balanced by the know-how of the equipment suppliers who judiciously exploit the possibilities of the modern symbols generators.

2.4. Towards the uniformisation of symbols

The review of the main historical concepts of HUD, together with the comparative analysis of existing HUD performed during the present study (paragraph 4.3), indicate that a set of symbol exist today, which knowledge and meaning are shared within the aviation community : a kind of common HUD language…

So, it is possible to describe the main elements of a generic HUD symbology ; those symbols can be identified among the majority of existing HUD, with some minor variations which are typical of each HUD supplier.

A description of the main analogue symbols found on most current HUD is provided in Appendix 4.

It should be noted that a symbol-by-symbol description is limited because it only provides a static shot of the HUD : an actual symbology should be evaluated according to its actual context of use and taking into account different aspects (dynamic, mode switches, compatibility with head down instruments,…). A generic description is only valid for use as a common language to allow some comparisons, but not as a specification of a standard symbol set.

3. HUD regulation : state, interpretation and project

3.1. Review of the existing regulations

3.1.1. JAA and FAA inventory

The collection of regulatory texts and existing rules concerning HUD symbology produced the inventory reported in Appendix 5.

3.1.1.1. Text organisation

As such, the inventory of HUD regulation appears to be quite contrasted : it is composed of numerous and various texts ; several factors have to be considered if one will to understand what are the principles of their organisation and which text has to be considered for a given need. Those factors are further discussed below.

In particular, the certification experts use their knowledge of the texts and their various factors when they have to establish the regulatory basis, which the set of regulation to be applied for the certification of a given HUD product.

Regulation authority

The authority issuing a given regulation is generally easy to identify ; for instance some are clearly JAA or FAA regulation.

A smaller number of texts is issued by national authorities ; this mainly concerns derogation from an international regulation and draft proposals for a change in the international regulation.

Some other organisation also produce regulatory documents ; for instance, SAE and RTCA in the USA provide technical specifications which are used as minimum standard requirements.

Even if the regulation authority is clearly identified, the applicable geographical extent of a given text is somewhat difficult to determine due to the intrication of the national transportation systems, despite the current harmonisation effort. Hence, it may happen that a JAA document is applicable in a FAA certification.

In all cases, the certification basis applicable for the certification process of a given HUD system is determined by the regulation experts, following negotiations with the involved industry and airlines.

The status

Some differences of status among the texts have to be noticed.

The status corresponds to its level of applicability, and to its date of issue when applicable :

- The main fundamental **applicable rules** are FAR 25, JAR 25, JAR AWO, JAR OPS et JAR HUDS 901, 902 et 903.

- Some other text propose **acceptable means of compliance** : this is the case of the Advisory Circulars : FAA AC (e.g. AC 25-11 for EFIS, AC 120-28D for category III operations and AC 120-29A for category I and II) and JAA ACJ. A difference exist between AC and ACJ : the ACJ are a integral part of the regulation, distributed as appendices to the JAR, while the AC are issued as separate application rules. Those texts may be accompanied by guidance material addressing some special issues, such as the FAA memorandum policies.

- When a particular problem is encountered during a certification process which is not covered by the existing rules, a special document is issued, such as the JAA Certification Review Item (CRI) and FAA Issue Papers (IP), which may then be used as a reference case for later certifications.

- Some texts are draft regulation, such as SAE ARP 5288 which is an American project for a specific HUD regulation.

- The last kind of text is composed of recommendations or **guides** (Human Factors Design Guide, Flight Test Guide). The Human Factors Design Guide provides some general notions and recommendations for user interface design, but it is not easily applicable to HUD specificities. For now, there is no HUD design guide, nor HUD certification guide…

It has to be noted that the regulation is continuously slowly evolving. The date when the certification request is published by the industrial usually determines which regulation will be applicable ; so the request is usually done as soon as possible.

The applicable stage

An other distinction between regulatory text is the design stage they address :

- **Design** : this is the case of JAR, FAR, SAE recommended practices (ARP) and RTCA documents ;

- **Certification** : this is generally the case for the acceptable means of compliance (AC, AMJ, ACJ) and also of the JAR AWO and HUDS which address certification objectives and methodologies ;

- **Operations** : JAR OPS 1 (subpart E : all weather ops including hybrid HUD) and 4 (subpart 3 : all weather ops with HUD guidance) which also address crew instruction and training.

This distinction may appear simplistic, as the designers of course take the certification requirements into account, which themselves are related to the operational context. Moreover, some texts address several stages, such as the FAR which include ACJ.

The type of instrument

A HUD is definitely a particular type of flight instrument. As such, a hierarchy of regulatory texts may be applicable :

- FAR 25 and JAR 25 (especially § 1303, 1321, 1333, 1335 et 1381), as a flight instrument ;

- FAA AC 25-11 and JAR AMJ 25-11, as an electronic flight instrument (EFIS),

- FAA AC 120-28D, 120-29A and JAR HUDS 901, 902, 903, which specifically address the case of HUD.

It has to be noted that some requirements generally applicable to flight instruments are not directly applicable to a HUD ; such as, for instance, colour requirements for warning indications. This is a reason why specific HUD texts have been published ; these texts provide supplementary requirements in order to compensate for the HUD specific characteristics ; for instance they may require that flashing should be used instead of red colour.

The operation category

The applicable regulation obviously depends on the operation category for which certification is to be obtained :

- FAR and JAR 25, JAR HUDS 903 are applicable to all operation categories ;

- supplementary regulation is applicable to low visibility operations :
  - FAA AC 120-29A, JAR HUDS 902 or JAR AWO subpart 2 for category II ;
  - FAA AC 120-28D, JAR HUDS 901 or JAR AWO subpart 3 for category III.

The phase of flight

The following flight phases are usually addressed because of their particular requirements for the use of a HUD : roll-out, take-off, cruise, unusual situation, approach, flare and go-around…

The concept of use

This last but crucial distinction corresponds to the concept of use under which the HUD is designed. Some requirements are applicable whatever is the concept of use, some are only applicable to one concept :

So are the JAA texts :
- for the monitoring and hybrid HUD concepts : JAR HUDS 903, JAR AWO, JAR OPS 1
- for the manual HUD concept, with guidance : : JAR HUDS 901, 902, 903, JAR OPS section 4, part 3.

The FAA text (AC 120-28D et 120-29A) are common to all three concepts, with special paragraphs for the hybrid HUD concept.

3.1.1.2. Synthesis of the inventory

A synthesis of the current regulation inventory is provide d in Appendix 6.

A general conclusion is that a linear lecture of the regulations is usually not easy nor relevant, due to the complexity of the existing regulation. Expertise and text interpretation are required from the designer and the certificator.

However, it is possible to identify the correspondences between the American and the European regulations applicable to the HUD, in order to proceed to their comparison, as described in the following table:

Operations	European text	American text
All	JAR HUDS 903	SAE ARP 4102/8 SAE ARP 5288 (draft)
Cat. II	JAR HUDS 902	FAA AC 120-29A
Cat. III	JAR HUDS 901	FAA AC 120-28D

The inventory of the regulatory texts applicable to the HUD is complex and involves several dimensions: regulation authority, status of the text, applicable stage, instrument type, concept of use , flight phase and operation category, among other…

3.1.2. Comparative analysis of the existing texts

This analysis has a double objective :
- first, try to identify the existing differences between the American and European texts;
- second, identify the direct or implicit requirements concerning the elements of the symbologies.

The analysis concerns the general rules from the basis regulation and then the differences between the regulations and specifications of HUD symbologies, by operation category.

3.1.2.1. Functional requirements

The regulation is fundamentally based on functional requirements that the equipment has to fulfil, such as shown in the extracts below :

> *"The design of the HUD symbols should provide for satisfactory manual control, or for monitoring of automatic flight, for the flight phases for which approval is sought. (…) The selected symbols should be consistent with the intended uses of the HUD." (JAA HUD 903).*

> *"The HUD must provide sufficient guidance information to enable the pilot to maintain the approach path, to make the alignment with the runway, flare and land the airplane within the prescribed limits or to make a go-around without reference to other cockpit displays." (FAA AC 120-28D, cat. III ops)*

In particular, the requirements concerning the human factors are generally addressed from a functional and subjective perspective, both in the American and in the European regulations. This is the case for several essential human factors dimensions for a HUD design :

- **workload** :

> *"The use of the HUD must not unduly fatigue the pilot (e.g., due to eye strain, maintaining a rigid head position, or excessive mental concentration). The work load associated with the use of the HUD must be considered in showing compliance with JAR 25.1523, ACJ 25.1523 and JAR 25 Appendix D." (JAR HUDS 903).*
>
> *"The workload associated with use of the HUD [guidance system] should be considered in showing compliance with section 25.1523." (FAA AC 120-28D, appx 2.)*

- **symbol interpretation** :

> *"Display elements and symbology (…) should be <u>natural</u>, <u>intuitive</u>, and <u>not dependent on training or adaptation</u> for correct interpretation." (AC/AMJ 25-11, 7.)*

- **situational awareness** :

> "*EFIS displays must be able to convey to the pilot a quick-glance sense of the present speed, attitude and altitude." (AC/AMJ 25-11, 7d.2i.)*

The American and European regulations also have adopted a common definition of human factors and promote the same approach to be used for their assessment in a certification process :

> *<u>"Human Factors</u>. Humans are very adaptable, but unfortunately for the display evaluation process they adapt at varying rates with varying degrees of effectiveness and mental processing compensation. Thus, what some pilots might find acceptable and approvable, others would reject as being unusable and unsafe. Airplane displays must be effective when used by pilots who cover the entire spectrum of variability. Relying on a requirement of "train to proficiency" may be unenforceable, economically impractical, or unachievable by some pilots without excessive mental workload as compensation." (AC/AMJ 25-11, 4b.1).*

Behind these subjective but essential requirements, the regulations also contain numerous explicit requirements on the pieces of information to be presented to the crew, and especially, on the elements of a HUD symbology, which are further described below. However, it has to be noted that even these explicit requirements are usually limited to a short mention of the nature of the information which should be displayed ; the format (analogue or digital), shape, size, or location of the symbol to be used is seldom provided.

3.1.2.2. Some similar basic rules : FAR and JAR 25, AC 25-11 and AMJ 25-11

The word-by-word comparison of the main sections of the basic rules concerning the HUD (FAR and JAR 25, AC and AMJ 25-11) only reveal some very limited differences ; indeed, the two regulations require the presentation of the same information pieces.

A small difference in the approach used appear through the first alinea of JAR 25.1303 concerning flight and navigation instruments, which is absent from the FAR:

> *"All flight and navigation instruments must have characteristics suitable for use in the particular aeroplane considered. The presentation must be clear and unambiguous."*

This may be significant of the general preliminary preoccupation of the European regulation which is to promote a clear and non ambiguous presentation.

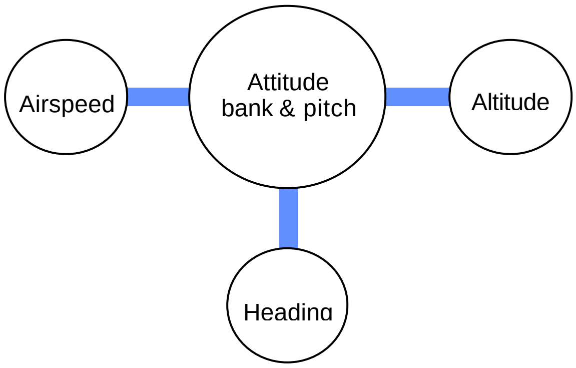
The rules applicable to the constitution of a HUD symbology are further analysed below.

Primary flight and navigation information : the basic T

The primary flight and navigation instruments are defined by FAR/JAR 25.1303. They include : air speed, altitude, vertical speed, bank and pitch attitude, rate of turn and direction.

All these information items should be displayed on a HUD used as a primary flight instrument.

These information items should be displayed using the well known 'basic T' arrangement :



This arrangement is specified by FAR/JAR 25.1321 :

> *(1) The instrument that most effectively indicates attitude must be on the panel in the top center position;*
> *(2) The instrument that most effectively indicates airspeed must be adjacent to and directly to the left of the instrument in the top center position:*
> *(3) The instrument that most effectively indicates altitude must be adjacent to and directly to the right of the instrument in the top center position; and*
> *(4) The instrument that most effectively indicates direction of flight must be adjacent to and directly below the instrument in the top center position.*

Note that the vertical speed is not an element of the basic T according to this rule, although its presentation is required by the rule 25.1303.

Electronic instruments specifications

The regulations concerning electronic flight instruments (AC and AMJ 25-11, 7a) have to be considered, as they are applicable to modern HUDs.

The chapter 5 of these documents addresses several key aspects of the display of information on electronic instruments and HUD a fortiori, in comparison to traditional instruments :
- **colour standardisation**: this recommendation is helpful to convey warning and improve differentiation between information items ; it is of course not directly applicable to the current monochromatic HUD ; which require a specific regulation covering this issue.
- **redundancy of symbol characteristics**: a discussion concerns the relationships between work load and information separation by means of colour ; systematic use of redundant coding (e.g. colour plus shape) is recommended ; this recommendation is applicable to HUD using shape, size and location as possible redundant parameters ;
- **symbology standardisation**: this standardisation is recommended, using SAE documents as possible references;
- **symbols location** : similarities between the cockpit instruments is recommended, and is directly applicable to HUD as an aspect of head down compatibility ;
- **clutter** : display saturation may increase the time required for symbol interpretation. Two ways are suggested to avoid this : use of simple symbology and limit the number of symbols to the

set required for the current task. The HUD specific issue of external world masking is not addressed.

The chapter 6 addresses some physical characteristics which are of primary importance for HUD design :

- **brightness level adjustment** : should be satisfactory under all possible lighting conditions ; this is critical for HUD in order to avoid possible masking of external view in low lighting conditions ;
- **update rate** : this parameter may affect the usability of the display in dynamic situations ; flicker and symbols lag are known to be especially annoying in the case of HUD.

The chapter 7 precisely addresses information display.
Beyond the fundamental “natural, intuitive and not dependent on training or adaptation for correct interpretation” recommendation, more precise recommendations are provided.
The basic T arrangement is retained ; deviations from this rule cannot be granted without human factors substantiation based on well founded research or extensive service experience.

The only difference between the FAA and the JAA documents concerns the transposition of the EADI and EHSI (sometimes the case in a HUD symbology) which is not found acceptable by FAA, while it has to be considered on a case by case basis by JAA.

The location and the format (digital vs. scales, reference marks,…), including their possible variations, are also addressed, and the special case of primary flight displays (PFD) integrating many flight information is subject to specific recommendations.

As a conclusion, the electronic instruments documents already provide many detailed recommendations on the basic symbology. Some of them are not directly applicable to the case of HUD, this is a reason why specific HUD regulations are required.

3.1.2.3. HUD specific regulations : SAE ARP 4102/8 and JAR HUDS 903

The HUD specific regulations have no direct equivalent on both sides of the Atlantic, contrary to the general rules (FAR and JAR 25) and to electronic instruments advisory materials (AC and AMJ 25-11).

The European document is the interim policy HUDS 903, issued in 1997, which is a part of JAR. This document provides criteria for the approval of HUD in order to assist HUD certification programmes.

The closest equivalent in the USA is the “recommended practices” document from SAE, ARP 4102/8 issued in 1998, and which refers to the JAA document. This document is intended to provide some minimum standard for HUD design, rather than guidance for certification.

Both documents address the case of HUD, collimated to infinity, conformal (with possibly non conformal elements) and without imagery (EVS is not covered).

Different uses of a HUD are distinguished : the HUD may be intended to replace (SAE : *replace*, JAR : *primary reference*) or to supplement (SAE : *repeat, augment*, JAR : *supplement*) the head down instruments.

Both texts are not clear concerning the possible concept of use (monitoring or manual).
Nevertheless, some elements provide indication on their founding philosophy :

- The SAE document requires flight guidance information within the basis symbology, and display of sufficient information to allow manual flight in the case where the HUD is used as a primary flight instrument.

- The JAA document mentions the uses of a HUD for manual control and for automatic flight monitoring ; however, the definition of *guidance*[1] appears quite ambiguous because it covers either the cases of manual control and monitoring...

JAR HUDS 903 addresses most of the issues specific to HUD : workload, pilot fixation, sources of confusion, clutter, non conformal positioning, compatibility with head down instruments ,mode selection and switching, consequences for crew task sharing, alert and failure recognition,…

The document emphasises the need to elaborate the symbology in accordance with the aircraft and with the intended use ; indeed, this approach appears to be more adapted than attempting to define a standard symbology set independently from its context of use.

The table in Appendix 7 compares the explicit requirements of the two documents, concerning the information item which should be displayed. These requirements are similar, except the extra requirement of the SAE document concerning guidance information.

As a conclusion, it appears that the SAE and JAA documents address different levels. The SAE document is more limited and less clear ; it does not explicitly address the use of a HUD for monitoring. The draft document SAE ARP 5288 which is considered later in this report may contribute to improve the American regulation.

3.1.2.4. HUD for cat. II operations : FAA AC 120-29A and JAR HUDS 902

Opposite of the text of the SAE applicable to the HUD for all operations, the American text for category I and II operations is a very complete text, intended for certification. It gives the conditions, performances, equipment, procedures, training and qualifications necessary to proceed to the approaches of categories I and II, including specifications for the manual or hybrid use of HUD and EVS... A parallel reading with the JAA text is thus relatively difficult because this one is specific to the HUD for category II operations.

The JAA text uses the same ambiguous definition of guidance as JAR HUDS 903 and the FAA text ; so it is applicable to HUD used either manual control or for monitoring of automatic control.

The text of the JAA appears clearer and more concise than the FAA text, also it covers a more limited field. Like JAR HUDS 903, JAR HUDS 902 formulates more qualitative requirements then the FAA text: It provides some performance requirements in relation to the operation concerned, rather than an explicit description of the information items required. Thus, the JAA text is organised by functional aspects (E G: " Go-around ", " Flight Crew Workload ", " Control of flight path ",..) while the FAA text uses a description by type of system (" FD systems ", " HUD systems ", " Hybrid systems ",..).

Concerning the concepts of use of the HUD, the FAA text appears to be more precise than the JAA text. For the manual concept, the FAA text specifies in particular that a guidance (flight director) must be presented, as well as situation information: typically, rough deviations from the ILS beam (5.5 and 5.9). The JAA text only specifies that guidance (in the broad sense) must be of sufficient quality.

Concerning the monitoring or hybrid concepts, the FAA text is also more detailed. It specifies that the hybrid systems (e.g. a fail passive autoland system used in combination with a monitored HUD) are also acceptable if they provide the equivalent performance and safety to a non hybrid system.

[1] *"Information used during manual control or monitoring of automatic control of the aircraft that is of sufficient quality to be used by itself for the intended purpose."* This definition is the same as in FAA AC 120-29a and 120-28d.

In the European text, the concept of hybrid HUD is not clearly clarified. It is necessary to note some common elements between the two texts: thus both use the same formulation to specify that the transitions (from monitoring to manual piloting, or from the HUD to head down instruments) should not require extraordinary skill, training or proficiency.

The comparison of the explicit requirements in Appendix 7 indicates the more explicit requirements of the FAA text, on certain points (markers indication, need for guidance, navigation sources, use of the HUD for ILS interception, flare and roll-out). Last, the two texts comprise the description of the criteria (performances) and of the methods (statistical) to be used for certification.

3.1.2.5. HUD for cat. III operations : FAA AC 120-28D and JAR HUDS 901

The regulation applicable to category III HUD operations are quite similar in their arrangement to the regulations applicable to cat. II operations.

It should be noted that:
- The FAA regulation also addresses the low visibility take off operations ;
- The JAA regulation only concerns HUD used for manual control ; hybrid HUDs are addressed by JAR AWO subpart 3. This last document is similar to JAR HUD 901 : it clearly defines the hybrid landing system concept and considers the HUD as a part of this system, which should contribute to the required safety level for the whole system, without necessarily satisfying the same criteria as the primary system (the autopilot).

As for cat. II regulation, the European text appears to be clearer than the American regulation, while the American regulation is more precise concerning hybrid HUD in comparison with the JAR AWO regulation ; moreover, the FAA regulation requires a proof of concept for hybrid systems, before their certification.

The explicit requirements of the JAA and FAA texts are compared in Appendix 7 ; the requirements appear similar, except some particular points : marker indication and navigation sources (not required by JAA), runway symbol and auto throttle mode (not addressed by FAA).

3.1.3. Draft American regulations : SAE ARP 5288 and FAA working paper

The SAE document is a draft regulation specific to HUDs, which main purpose is certification (while SAE ARP 4102/8 primarily addressed design); it addresses most of the HUD specific questions, from their technology and design up to their evaluation.

This text is organised according to functionalities, such as FAA AC 25-11 and JAR HUDS.
Its main chapters are :

1. Scope
2. References
3. Display function
4. General design consideration
5. Equipment installation
6. Display visual characteristics
7. Information display
8. Information separation / Symbology presentation
9. Sources and annunciations
10. Verification considerations
11. Glossary of terms

The main elements concerning HUD symbology design and evaluation are detailed below.

The third chapter distinguishes <u>3 possible types of HUD applications</u> :

- Supplemental use : A HUD may be used to supplement flight deck instrumentation for use in the performance of a particular task or operation, without replacing the conventional head down flight deck information. An example use is pilot monitoring of a visual approach, airspeed, altitude, angle of attack, and autopilot performance;
- Alternate use : A HUD may be used as an alternate source of primary information ; this information should be presented in a manner such that the pilot can rely on the information presented by the HUD, in lieu of scanning the conventional head down instruments typically used for the task to be performed. As an example, a pilot may use a HUD approved as an alternative means to verify the performance of automatic flight control systems, without frequent reference to head down displays and instruments.
- Additional credit use : A HUD may be used to provide information for use in the performance of a particular task or operation which adds to the current authorisations of a particular aircraft. For these tasks or operations, the required information will be displayed on the HUD in lieu of the head down instruments. As an example, additional credit approval of a HUD could be used to conduct operations to lower minima than currently authorised for a particular aircraft or automatic flight control system

A HUD, depending on its type of application, may be considered the primary flight reference when the pilot is flying “head up”. The information displayed on a HUD used as a PFR should include as a minimum, the basic T specified in FAR 25.1321. Other components required for display on a HUD are dependent on the other phases of flight and flight operations, and on its use either for monitoring or for manual control.

Chapter 6 gives some criteria for Functional Hazard Assessment (FHA) concerning the different information items displayed on the HUD, depending of the type of application and of the operation category.

Chapter 6 addresses the visual display characteristics required for the HUD : external symbol positioning accuracy, line width, luminance, dynamics. In particular, the symbology lag shouldn’t exceed 100 ms. This chapter also addresses some issues raised by raster imagery.

Chapter 7 discusses the choice of information to be displayed and contains several adaptations of the basic regulation to HUD specificities :

- The basic T arrangement is required except proof of concept. Some examples of possible deviations are mentioned : vertical speed scale between the altitude and attitude displays, placing the heading above the attitude display, moving speed value indication.
- Pitch attitude should be displayed so that the horizon reference line remains visible during all manoeuvres.
- An indication of the velocity vector is considered essential to most HUD applications. It may be inertially or air mass derived, and the type of flight path may depend on the phase of flight.
- Some indications required by the FAR to be displayed for certain phases of flight could be displayed only part time ; an equivalent level of safety to the full time display should be demonstrated.

Chapter 8 concerns information symbology and information presentation :

- The application of ‘standard’ commonly used symbology is recommended.
- Clutter is qualitatively described as in AC 25-11, with no more precise criteria ;
- Attention getting techniques and means to compensate for the lack of colour are discussed,
- Head up / head down display should be consistent, but do not need to be identical. Some further guidelines are provided.

Chapter 9 deals with sources and annunciations : navigation sources and mode annunciation, alerting issues, including TCAS, GPWS and *windshear* which should be presented on a HUD used as a PFD.

Chapter 10 provides several verification considerations, the first of which is human performance testing, emphasising human variability (like AC 25-11), test program duration and personnel, simulation environment and limitations, plus methods and criteria for unusual attitude recovery testing.

A glossary of specific HUD issues is provided at the end of the document.

This draft document calls for the following comments :
- The definition of three types of HUD applications is useful to complete the notions of primary or secondary instrument ;
- The document contains some specifications on the constitution of the basic symbology of a primary HUD system ; some supplementary recommendations apply to the use as a monitoring system or as a manual control system. Reference is made to the existing regulation, especially for low visibility operations (AC 120-29a and 120-28d).
- The document addresses most of the aspects considered during certification : readability, clutter, risks of confusion, consistency across the cockpit, dynamics, alerting,… Useful guidelines are also provided concerning the certification process.
- The guidelines are quite exhaustive although they remain qualitative ; they emphasise the necessary consistency between the HUD product and its intended context of use ; so, a large part of the final decision is left to the expertise of the certification experts.

This draft SAE document is likely to compensate for the lack of general HUD regulation document in the American regulation. It is similar to the JAR HUD 903, but more complete : it addresses most of the HUD issues, while leaving a large part to the judgement of the certification experts.

An other draft document is a FAA working paper concerning HUD certification criteria, which makes reference to the existing FAA and SAE document, among which the draft ARP 5288.

The motivation behind this document is to complement the AC 25-11, regarding the HUD specific issues. It provides some precise specifications about the following points : required information, use and format of scales, unusual attitudes, visual take-off format, airspeed markings, cockpit compatibility, clutter and dynamics… It also provides some specifications concerning the certification methodology, namely, safety analysis.

This document call for the following comments :
- It doesn't mention information conformity, nor flight path indication, while they are some essential HUD features ;
- The document requires that the specifications for a HUD used as a primary flight instrument must be considered where it can be reasonably expected that the pilot will operate primarily by reference to the HUD. This point seems to be worth considering in order to better take the actual use of the HUD into account, rather than limiting the scope to the prescribed use.
- Several specifications refer to precise context of use (for instance, concerning the visual take-off), which shows a relevant experience of the use of the HUD.
- The document especially insists on the failure recognition and on the danger of the display of misleading information.

This draft document appears like a useful complement to the existing FAA AC 25-11, addressing several HD specific issues and inspired by actual certification experience. Although some aspects are missing, the integration of this document into the existing AC already harmonised between FAA and JAA may be easier than the addition of a new document such as the draft SAE ARP.

3.1.4. Synthesis on the existing regulation

The analysis of the **general rules**, not HUD specific, shows only some minor differences between the American and European regulation.

Among these texts, the EFIS regulation already provides some relatively detailed specifications concerning the constitution of the basic flight and navigation symbology.

The **texts applicable to HUDs** contain some adaptations taking into account the specificities of this kind of instruments ; their comparison shows larger differences, depending on the intended type of operation.

Nevertheless, this comparison indicates a consensus about the fundamental HUD characteristics :
- Monochromatic, collimated at infinity, conformal to the external vision;
- Necessary consistency between head down and the cockpit environment ;
- The information to display first depend on the category of operation and on the concept of use (manual control or monitoring).

Some differences identified between the explicit requirements of the American and European regulations are reported in Appendix 7, depending on the type of operation. These difference are summarised in the table below :

	FAA	JAA
Radio Altitude (all ops)	Recommended	∅
Energy state (all ops)	Recommended	Required
Excess ILS deviation (cat. II)	Recommended	Required
ILS Marker Indication (cat. II)	Required	∅
Navigation sources indication (cat. II)	Required	∅
ILS Guidance (cat. II manual)	Required	Optional
Auto throttle mode (cat. III)	∅	Required

These differences appear to be quite limited ; they probably more indicative of the different levels of the texts, rather than of significantly differing approaches of the use of HUD.

Two main points can be drawn from the comparison of the HUD specific regulation :
- The JAR HUDS appear clearer and better organised ; they address the functional issues, rather than the physical aspects of the equipment, which seems to be a better adapted rationale ;
- The FAA regulation provides several supplementary requirements regarding the use of hybrid HUD, including the required proof of concept for category III operations.

As a conclusion, the differences between the American and the European regulation remain minor ; some more significant differences between the approaches of HUD should be rather looked for at the level of **interpretation** by the experts.

Last, an effort is carried out by FAA to compensate for the lack of a general HUD document. Two draft texts are worth considering in an attempt to harmonise the HUD regulation : the new SAE ARP 5288 and the FAA working paper on certification criteria.

3.2. Regulation interpretation during certification

3.2.1. The certification process

The certification process usually depends on two possible certification contexts :
- the certification of a new aircraft, where the HUD is proposed as a possible equipment ; in this case, the candidate is the aircraft manufacturer ;
- or the certification of a HUD product as a new equipment of an already certified aircraft ; in this case, the candidate is the HUD manufacturer.

The candidate has a crucial role in the certification process : he has to :
- propose a test program, using the **regulation basis** which is established together with the regulation authority ;
- provide funding for the test program ;
- follow and adapt the product according to the requirements of the certification team.

Generally speaking, the certification cyclic process aims at assessing the limitations, the possible traps and inconsistencies of the technological product in the context of its intended use. Some technical adaptations may be required and implemented by the candidate manufacturer. The goal is to optimise the process by using the adequate evaluation support (paper document, simplified simulator, full mission simulator, flight tests) and by reducing the number of changes. The economical constraints induce a tendency to focus the evaluation on the suspected most critical issues for safety (extreme conditions, technical failures, false human inputs), even if they're very seldom met in reality.

The certification team is usually composed of one test pilot and one test engineer. The team work is especially important in the case of HUD certification, as the information displayed in the HUD is visible only for the pilot : the HUD is definitely a human-system information means, not a support for internal crew exchanges.

3.2.2. Interviews of certification experts

Partially directed interviews were conducted with two test engineers and two test pilots having a HUD certification experience. Some questionnaires were designed in order to capture the problems of these two populations (Appendix 8 et Appendix 9).

The certification objectives are determined by the regulation :
- The rules provide the reference framework. They contain some precise specifications concerning HUD symbols. Most of the time, however, their requirements remain at a generic level, so that innovation is possible and they primarily address design and safety principles (the spirit of law).
- The existing draft regulations are most of the time taken into account.
- The published issues of previous certification experiences have a status of regulation ; the certification of an equipment certified in an other context is limited to a check of its adequation with the new context.

Because of the genericity of the requirements, there is of course room for different interpretations among the certification experts :
- Some give priority to clutter minimisation and accept that an information is not explicitly displayed, if it is possible to derive its value from the other symbols ;
- Some other, mostly Anglo-Saxons, require each information explicitly required to be displayed separately, leading to a direct copy of the head down instruments, including digital values and analogue scales with marks and labels, for instance.

The interviews highlight the main HUD certification objectives :
- Check the reliability of the symbols (e.g. velocity vector lag during rotation or go around, which may impose to revert to attitude instead of flight path control) ;
- Check that the performance objectives are met for the different intended operations and expected conditions ; the HUD is always globally evaluated from a performance point of view ; the HF aspects mentioned in the regulation are not directly addressed, but implicitly ;
- Identify the possible risks of confusion error in symbol interpretation (e.g. static and dynamic ; field of view limitations)
- Avoid clutter (symbols shape and size, use of intuitive analogue formats, 'declutter' mode) ;

- Examine the limits of use (unusual situations, symbology lags, input errors and failure cases) ; this emphasis on the particular conditions of use raises the question of the conditions of use : a format usable in these conditions may be not the better adapted for usual conditions.

Some limitations of the existing regulation were pointed out during the interviews :
- The piloting reference frame is generally not specified (e.g. flight path and pitch attitude for go-around), nor the symbology switches from one flight phase to another;
- The regulation generally provides few indications about the concept of use;
- The unusual situations are not precisely addressed, also they require special symbologies and evaluation ;
- The regulation provides only a few indications concerning the choice of the pilot population involved in the evaluation (inter and intra individual variability).

However, the certification experts draw attention on the drawbacks of a too much restrictive regulation, regarding innovation and latitude of expert judgement.

Because of the limited information contained in the regulation about human factors, the certificator's experience is prevailing for their evaluation, especially about :
- the context of use of the HUD ;
- the characteristics of the intended users, which are summarised by the notion of 'reference pilot', and include their habits, way of life, discipline, preferences,… ;
- the knowledge of the HUD specific traps, and of the possible previous incidents or accidents happening when using such a system ;
- the evaluation methods (choice of relevant criteria, choice of the subjects, design of the test program, occurring events,…).

This expertise is crucial to orient the test program towards the possible weaknesses of the system, which still have to be objectively proved.

A comparison of the opinions of two test pilots concerning the relevance of different symbols is shown in Appendix 10. This comparison shows that :
- Different opinions may exist even among a small number of certificators, sharing a common philosophy of HUD design;
- These differences are usually justified by the 'reference pilot' model ("I know that some pilots are using this information and may be disturbed if it is not explicitly displayed, even if it is possible for me to derive it from the other symbols").

3.3. Synthesis about the existing regulation and its interpretation

The comparative analysis of the existing regulation doesn't show deep differences between JAA and FAA concerning the design, the evaluation or the use of the HUD.

The existing regulations do address most of the issues raised by the constitution of HUD symbologies. On an other hand, the regulations appear complicated and quite confused because of the number of regulatory documents to be considered and because of their numerous intersections. The JAA regulation (namely, JAR HUDS 901, 902, 903) uses a functional approach and appears better organised, except perhaps when addressing the case of hybrid HUD, which is covered by JAR OPS.

The American draft documents (SAE ARP 5288 and FAA working paper) are worth considering : they use a similar approach to JAR HUDS, and they go further in the description of HUD specific issues and possible future evolutions such as EVS or dual HUDs.

The interviews conducted with the certification experts reveal strong convictions about the role of a HUD and on the interpretation of the regulation, based on their personal operational or certification experience.

However, the recent certification programs do not show many differences between the FAA and JAA certification teams : both organisms have certified the same HUDs presented very complete symbologies.

One point is that the French certification experts met during this study are not necessarily representing the majority of JAA certificators, who do not share the opinion of the need for intuitive, uncluttered symbologies.

A general issue is linked to a misconception of the HUD as a traditional PFD : a “transparent PFD”. This conception is symptomatic of a paradoxical opinion of pilots who don’t want clutter but would like to see many information items on the HUD for their different needs. It is also linked to the ambiguity of primary means, which may be understood as the HUD being a stand alone system, or just as a regulatory requirement concerning the reliability of the information displayed, which should be similar to the reliability of the information displayed head down.

As a conclusion, the following issues can be proposed to improve the current JAA regulation :
- ♦ try to clarify the regulation, by associating the regulatory documents specific to HUDs ;
- ♦ precise the different concepts of use and organise the regulation based on these concepts;
- ♦ prepare some supplements to the existing regulation concerning the new concepts ;
- ♦ establish some criteria and methods applicable to HF issues during HUD certification (this point is further addressed later in this report).

4. The HUD in operations

Two main sources were used concerning the actual operational use of HUD, and more precisely concerning qualitative or quantitative data on the specificities and difficulties encountered on air lines :
- The analysis of accident/incident databases existing in various civilian and military organisations;
- The analysis of the existing symbologies actually in use, including their concept of use, their description and the opinion of their users.

4.1. Analysis of accident/incident databases

Several information sources are currently available :

On of them is general and collects voluntarily and confidentially reported incidents by the aeronautical actors, whether civilian or military, North American or others : the Aviation Safety Reporting System (ASRS), managed by NASA by request of FAA.

Two military databases were used :
- Vortex is a confidential and volunteer reporting system of the Flight Safety Office of the French Air Force (Bureau Sécurité des Vols de l'Armée de l'Air)
- Baséac of IMASSA collects the Human Factors analyses of all the accidents cases happening in the French Air Force.

Last, the Flight Analysis service of Air France was consulted. this airline operates around 40 HUD equipped aircraft.

The results of this review are presented below.

4.1.1. ASRS

According to the information request addressed to ASRS [ASRS, 2001], only 16 reports among about 100 000 reports collected since 1990 appear to be related to HUD. A synthesis of these reports is provided in Appendix 11.

It must be noted that the current ASRS form has some fields concerning the aircraft equipment with FMS/FMC or EFIS, but none concerning the equipment with a HUD.

However, only a very small number of events are reported concerning the use of HUD, in a ten years period. These events are also quite heterogeneous :

- In 8 of these events, the HUD has no direct relationship with the reported event ;
- In 2 of them, the reporter declare that the HUD was helpful because of the precision allowed in the piloting actions (high turbulence level and collision avoidance during take-off).
- In one of them, the reporter would have like to have a HUD available ;
- The remaining 5 reports actually concern some problems encountered in the use of a HUD or as a consequence of its use.

Several groups may be distinguished among the reported problems:

The symbology do not match the actual situation and the pilot notices it lately :

(1) On a fighter aircraft, the HUD symbology gets fixed because of a system failure, resulting in a stall ;

(2) The PF thinks that the PNF is in control using the HUD, although the control do not reveal a mistake in the inputs made by the PF, resulting in a low quality approach.

A symbol disappears during a flight phase were it is expected :

(3) An inadvertent use of the HUD test mode during a cat. III approach removed essential information…

(4) A guidance symbol disappeared during an approach, resulting in an altitude deviation.

Over focalisation on the HUD symbology, resulting in deficiencies in the control of the symbols validity :

(5) The FO considers that the HUD retained the PF attention during a go around commanded by ATC, which combined in a lack of traffic information resulted in a TCAS alert.

It is of course not possible to draw any conclusion about the actual difficulties in the use of a HUD from these reports.
Two possibilities arise from the lack of data available :

- either there is indeed no difficulty in the operational use of the HUD today ;
- or the HUD are only very seldom used in operations.

4.1.2. Baséac

The use of a HUD is never cited in an accident report of this French Air Force database.

4.1.3. Vortex

The Vortex database which collects voluntary reported events form the French Air Force doesn’t allow a precise search request concerning the implication of HUD in the events.

4.1.4. Flight Analysis at Air France

The systematic flight analysis office at Air France doesn’t have any particular safety report concerning the use of HUD. One should note that there is no special field on the presence of a HUD in the flight recording data, which makes a HUD specific request impossible.

Through these various information sources, the HUD doesn't appear today as a safety issue, which may be explained either by the actual safety level provided by the use of a HUD, or by the seldom use of the HUD in the actual operations, or by the possible reluctance of the users to report difficulties closely linked with their basic flying skills, or also by the lack of HUD specific fields in the reporting systems.

4.2. Review of existing HUD symbologies and opinions of their users

4.2.1. Methodology

This review of the existing HUD products is organised following the classification of the HUD depending of the concept of use under which they are certified :

- **monitoring HUD** : optional monitoring of the auto pilot for cat. IIIb approach,
- **hybrid HUD**: mandatory use for approach monitoring in cat IIIa/b with possible reversion to manual control in case of an autopilot failure
- **manual HUD**: cat IIIa approach under manual control using the HUD guidance.

In fact, a HUD certified for monitoring cat. III b approaches may also be used as an aid for VMC approaches for instance : the classification above relates to the most severe concept of use for which the HUD has been certified.

The technical documentation on the existing HUDs collected during this study is listed in Appendix 12.

These HUD products are classified according to their concept of use in the table below. The aircraft type is indicated, in italics if some complementary information have also been collected from their users. In parenthesis the certification authority and date are also provided.

Monitoring HUD	Hybrid HUD	Manual HUD
HUD Sextant (DGAC 1989) *A320 Air France*	HFDS Sextant MD 82 Alitalia (RAI 1997), *B737 l'Aeropostale (DGAC 1995)*	VGS BAe Systems B737 NG (FAA JAA 1997) HGS Flight Dynamics B737 NG (FAA JAA 1997) *CRJ Brit'Air (FAA JAA 1995)* Falcon 900 EX (JAA 1999)

The following aspects are addressed for each of the three possible concepts of use :

- The objective and motivation behind the concept.
- The main typical elements of the symbology attached to this concept (a detailed comparative analysis is provided later in the report).
- The opinion of the airline users met during the study (generally a experienced user was designated by the airline to answer our questions ; partially directed interviews were conducted, on the basis of the questionnaire provided in Appendix 13).

4.2.2. The monitoring HUD (HUD A320)

4.2.2.1. Concept of use

The HUD developed by Sextant for the Airbus 320 is an example monitoring HUD.
Historically, this HUD was certified in 1989 as a hybrid HUD for cat. III b approaches, before the aircraft was certified for this category without the HUD.
Today, this HUD definitely appears like a monitoring HUD when compared to more recent HUD products ; at Air France, its use is left as an option for the crews.

4.2.2.2. Description of the symbology

The A320 HUD symbology is dedicated to the monitoring of the automatic cat. III b approaches.
A typical example of this symbology during such an approach is presented on figure 4.

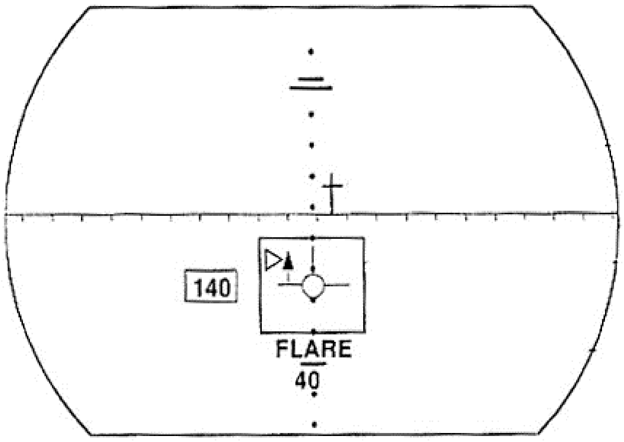


Figure 4 : an example monitoring symbology (HUD A320)

This symbology only displays the necessary information for the task.
The task consists in checking that the velocity vector stays inside the maximum ILS deviation box.
If this is not the case, the pilot has to recover manual control an proceed to a go-around.

This particular symbology has several special features :
- no indication of the heading, no graduation on the horizon scale ;
- no indication of the barometric altitude ;
- pitch scale in dots with no labels;
- speed deviation presented as a triangle moving vertically, and acceleration displayed as a vertical arrow.

This HUD also provides different symbologies for visual approach, take-off and landing roll-out.

4.2.2.3. Opinion of the users

The user interviewed

The user met for this study has been an Air France A320 pilot for 10 years and flight instructor for 8 years. He also flew on the Caravelle and Mercure aircraft.

History of the use of HUD

About forty A 319/320/321 are equipped with HUD. They were all ordered by Air Inter in 1988 for the continuity in the use of HUD as on the Mercure aircraft. The fleet is now used for the flights departing from Orly airport.
On Mercure, the certified approach minima were 35 ft DH and 125 m RVR, with the HUD.
On A320, the certification was initially, in 1989, of 20 ft DH and 75 m RVR with the HUD.
Since then, Airbus obtained the certification without HUD with the same minima.

Recommended use in the airline

The following functions of the HUD are pointed by the airline :
- On ground guidance for low visibility take-off
- Aid for visual condition approach
- Monitoring of cat. IIIa and IIIb approaches
- Monitoring of the speed and deceleration during automatic landing roll-out ;

- Guidance and monitoring of the speed and deceleration during manual roll-out.

As only a part of the A320 fleet is equipped with a HUD, the current procedures only recommend the use of the HUD when it is available, except for low visibility take-off for which the use of a HUD is mandatory.
The table below describes the prescribed use of the HUD and its limitations (M=manual ; A=autoland ; NP=not for use) :

The use of the HUD is :	Operation									
	taxi	take-off	cruise	appr. VMC	appr. cat. I	appr. cat. II	appr. cat. III	go-around	engine failure	unusual sit.
Mandatory	NP	M**								
Recommended*	NP			M	M	A	A		NP	NP
Possible	NP		M A***						NP	NP
Forbidden	NP							M or A	NP	NP

* If a HUD available...
** For low visibility operations, down to 75 m or 100 m RVR up to rotation.
*** For heavy clouds separation.

The main limitations of use concern the take-off rotation and the go-around, for which the use of the HUD is forbidden because of the lack of labels on the pitch scale.

Actual use

The generalisation of the results of this single interview is obviously to be taken with care.
It seems that the HUD is indeed use as intended for in flight and on ground phases in IMC conditions (cat. III). The concept of monitoring is especially interesting in order to reinforce the control of the automatism by comparison to the external cues.
Some limitations of the symbology have been mentioned, for the case where it would be used for manual control :

- the bank angle is difficult to evaluate precisely ;
- the current heading value is not displayed (also it is an element of the basic T) ;
- the pitch scale is not labelled, which may be a source of confusion (rotation and go around are forbidden using the HUD for this reason).

User needs

The fact that this symbology is very light has several advantages:

- a better external vision ;
- dispersion of the actual uses is not likely ;
- all symbols are perceived, so missing a change in the symbology (system failure) is not likely.

The operational gain only concern the low visibility take-off (75 m RVR, instead of 125 m) ; this gain is not economically measurable, because these operations are very seldom used (the interviewed user practised them 2 or 3 times over ten years).
The benefit is also for operations on terrain where the runway markings are limited (e.g., Brest or Biarritz).

Training issues

As the HUD is for the left seat, only the chief pilot may use it. The instruction for its use is integration in the qualification to the aircraft type, first for visual operations, then during the LVP operations training.
At the beginning, some pilots have difficulties because they focus too much on the symbology. Learning to keep the brightness at a minimum level is a crucial point.
All chief pilots periodically have to follow a training course in the simulator. The four A320 simulators of the airline have been recently equipped with the HUD, which is the only new equipment that the chief pilot have to learn using. The simulated flights consist of 3 or 4 take-off and approaches, with no presence of external traffic.

Populations and habits

The users have different opinions on the utility of the HUD, depending how they are used to it. Most ex-Air Inter pilot do use it ; there is an affective content associated with the HUD. Some of the older Air France pilots have been able to integrate it in their usual practice.
Usually, the pilots using the HUD feel less comfortable when the HUD is not available.

Safety benefits and operational feedback

On the modern glass-cockpit aircraft, it is quite frequent to see the crew focusing on the head down instruments (PFD and ND), to the detriment of the external vision even in visual conditions. The HUD has the potential to avoid this, it provides the external vision together with some very precise piloting cues. This may be very useful, especially when approaching airports with a busy traffic.
In the A320, the radio altitude is displayed on the HUD below 8000 ft, while it is displayed on the PFD only below 2500 ft : this is a very useful for CFIT prevention.
The HUD may contribute to avoid some incidents. For instance, in VMC, the detection of possible wind gradient at low altitude may be anticipated using the potential flight path information.
Up to now, the operational feedback sources provide no information about the use of the HUD during approaches. There is no precise measure available concerning the benefits of the HUD (e.g., the number of take off and approaches which wouldn't have been possible without the HUD).
The fact that the HUD will be maintained in a part of the fleet is a positive sign : the system is difficult to justify economically but it actually contributes to flight safety.

Possible improvements

It could be useful to have some vertical guidance for vertical avoidance, as provided by the TCAS or GPWS, or in case of wind shear.
Also, a vertical view of the terrain provided by a GPWS could improve terrain awareness. The same for clouds using the meteorological radar.
The field of view (+/- 10° horizontal) is too small especially for cross wind approaches : the velocity vector is then caged and flashing.

Perspectives of use

There is no retrofit planned for the part of the fleet non equipped with HUD. The equipment of the future aircraft with HUD will be envisaged.

4.2.3. The hybrid HUD (HFDS B737 or MD82)

4.2.3.1. Concept of use

The HUD from Sextant on the B737 of l'Aeropostale and the MD-82 of Alitalia belongs to the hybrid concept. It is certified for cat. IIIb approaches, while the aircraft with no HUD is only certified for cat. IIIa operations. The HUD also allows a reduction of the minima at take-off.

4.2.3.2. Description of the symbology

A typical symbology for an automatic ILS approach is presented on Figure 5.

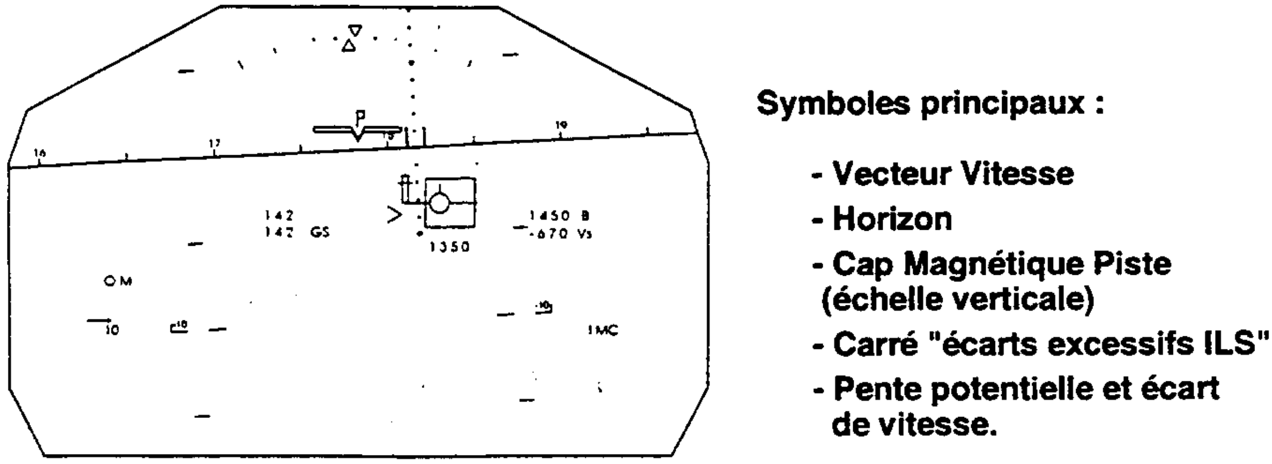


Figure 5 : Example of hybrid symbology (HFDS Sextant on B737).

This symbology is limited to essential information :

- a velocity vector surrounded with the numerical values from the basic T ;
- an horizon line labelled every 10 degrees and a simple pitch scale ;
- the runway heading and the excessive ILS deviation box, where the velocity vector should take place ;
- a potential flight path chevron and a speed deviation bar allow the monitoring of the auto throttle function and of the selected speed;

4.2.3.3. Opinion of the users

The user interviewed

The user met for this study is a chief pilot and simulator instructor at l'Aeropostale. He uses HFDS Sextant on the B737-300.

History of the use of HUD

The HUD are in use at l’Aeropostale since their certification in October 1995.
The airline actually participates to their certification. An issue encounetred during the certification was the lack of pitch cues for use of the HUD during go-around with engine failure : a special symbology was then developed (X pitch scale)

Recommended use in the airline

The HUD is used under two modes : either for autopilot monitoring in IMC with manual control recovering in case of excessive ILS deviation (hybrid use), or as a primary flight instrument in VMC and manual control.
In IMC, the HUD is certified down to cat. IIIb. and allows for a reduction of the minima :

	without HUD	with HUD
take-off	RVR 125 m	RVR 75 m
landing	RVR 200 m (cat IIIa)	RVR 125 m (cat IIIb)

Actual use

In fact, the reduction of the minima is seldom encountered in the usual operations at l'Aeropostale.
The HUD is also very useful for in VMC :

- to avoid disorientation during night operations over water ;
- to improve the precision of the approach in degraded conditions (for instance, operations on runway under maintenance)
- to evaluate the climbing margin using the potential flight path information (for go-around, in cruise for clouds avoidance, or in case of engine failure).

Training issues

The initial training and user familiarity with the system raise several issues :

- the confusion between the velocity vector and the pitch angle is typical, e.g. during take-off rotation;
- a misunderstanding of the go around symbology may appear if one is not trained ;
- also, some old pilots of Mercure aircraft have difficulties with the inertial velocity vector (air mass derived on the Mercure).

Populations and habits

When the HUD arrived in the airline, all pilots were expected to use them. Today, the use of the HUD is limited to the more convinced users. This evolution is due to the small number of HUD actually available : only 15 have been delivered and there has been relatively frequent failures (mechanics of the combiner, control buttons,…) with long reparation delays because of the small production…

A HUD qualification is included into the cat. IIIb periodic qualification that the pilots have to follow every six months. There is no typical profile for the HUD user.

Safety benefits and operational feedback

There is no specific feedback concerning the use of the HUD.

The use of the use is especially useful for safety in VMC conditions.

Possible improvements

The concept and the symbology of this HUD appear satisfying for the intended use.

The brightness adjustment could be improved to avoid the masking of runway markings in dark conditions.

Perspectives of use

The use of the HUD has to be considered in the frame of the integration of the airline in Air France.

4.2.4. The manual HUD (HGS on B737 NG and CRJ, VGS on B737 NG)

4.2.4.1. Concept of use

These HUD from Flight Dynamics and BAe Systems belong to the manual concept. They're designed for use as independent piloting instruments. They provide several modes of symobology in order to cover all possible flight phases.

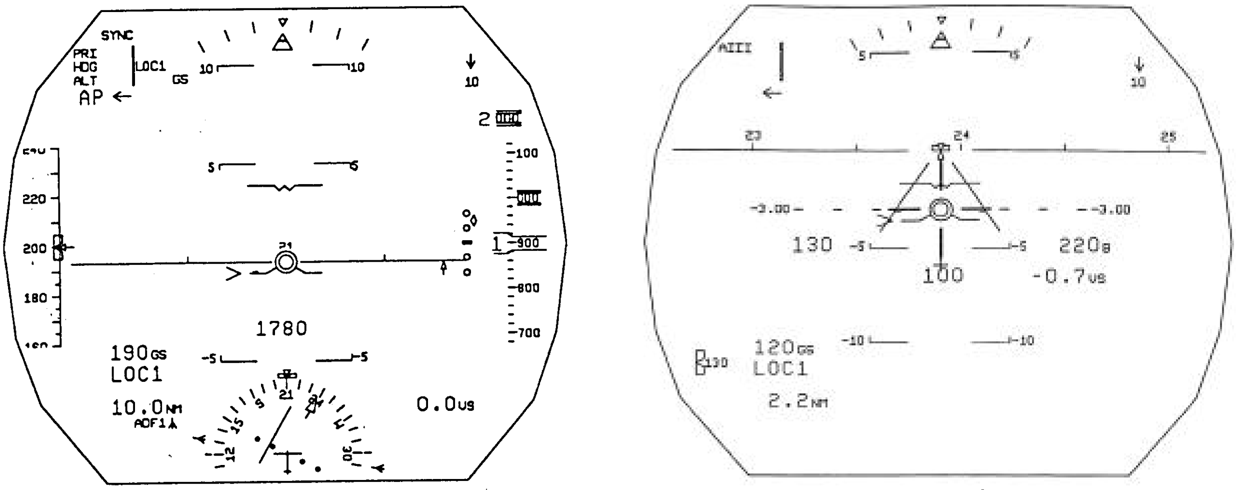
Their use is mandatory to proceed to cat. IIIa approaches : in this mode, they provide a flight director animated by a specific guidance law , which is redundant with the basic aircraft guidance used by the copilot to cross check the approach.

These HUD are self monitored : the monitoring functions integrated in the HUD computer are able to detect the possible sensor failures and the deviation from the nominal trajectory.

These HUD may also be used for the monitoring of the autopilot, during the flight phases where its use is authorised.

4.2.4.2. Description of the symbology

The typical manual HUD symbology for in their primary and cat. IIIa approach modes are reproduced on Figure 6.



PRI mode AIII mode

Figure 6 : Typical symbologies of the manual HUD concept (HGS du CRJ).

These symbologies are very complete. They have the following main particularities :

- in the cruise mode (PRI), speed and altitude scales with markings and target values, similar to the scales of the PFD, plus an HSI rose ; these symbols are removed in the approach mode ;
- complete information on the autopilot modes and on the navigation sources ;
- the flight director which is a small circle on which the pilot has to put the velocity vector ;
- the raw ILS information is also provided.

The symbology in the approach mode is usually lighter than the primary symbology : the choice of a declutter mode is left to the pilot only on the HUD proposed by BAe.

4.2.4.3. Opinion of the users

The user interviewed

The user met for this study is a chief pilot and instructor on the CRJ aircraft at Brit'Air. He has been a military pilot on Mirage III and on Mirage 2000 for 6 years, which gave him a favourable opinion to the use of a HUD.

History of the use of HUD

Brit'Air uses the CRJ 100 aircraft since 1995. All the aircraft were equipped with the Flight Dynamics HGS 2100 in 1996.
Then, the manual concept of use for cat. IIIa approaches was a new certification case in Europe. The airline didn't participate to the HUD design but was implied into the certification. The procedures proposed with the HUD have been adapted to the use of the airline.
The aircraft manufacturer is not deeply interested into the HUD because of the small market (no use of the HUD on this aircraft type over the Atlantic). that's the reason why the HUD has only been approved for approach and landing operations up to now (PRI and cat IIIa modes). The certification is now under extension for the other modes.

Recommended use in the airline

All the chief pilots of the airline are qualified for the use of the HUD for cat. IIIa approaches, which is mandatory between 200 m and 300 m RVR, down to a minimum of 50 ft DH. The use of the HUD is recommended for most flight phases, and especially for training to cat. III approaches.
The table below summarises the use in the airline (M=manual; A=autopilot monitoring) :

Use in the airline :	Opération									
	taxi	take-off	cruise	appr. VMC	appr. cat. I	appr. cat. II	appr. cat. III	go around	engine failure	unusual sit.
Mandatory							M			

Recommended	M	M*	M/A	M/A	M/A	M/A		M	M	M
Possible										
Forbidden										

* only as an help for visual take-off.

Actual use

The HUD is actually not much used, except for the cat. III ops where it is mandatory.
That's an issue, because it is better to be used to it.
Notice that if the HUD was always used, then it could be difficult to come back to the use of the classical head down instruments if the HUD were to fail.

Training issues

Training is provided in the simulator from VMC approaches to cat. III approaches. The use of the HUD is easy. Over focalisation on the HUD may be avoided by training and an appropriate brightness adjustment of the symbology.

Populations and habits

The pilots' appreciation of the HUD depends on their age and experience.
Generally they're satisfied, even if the HUD is seldom used, which is an actual issue.
The younger pilots are usually more interested into the HUD : they adapt more easily to automation. Also, the pilots coming from the Air Force are convinced of the benefits of the HUD.
The line on which the pilots operate generally has no influence.

Safety benefits and operational feedback

The operational benefit is difficult to quantify : approaches with less than 300 m RVR are seldom used. The ratio of re routing and cancelled take-off is very low. There is no way to know the number of approaches or take-off allowed by use of the HUD, as there is no specific feedback concerning the use of the HUD.
For each cat. III approach, a reporting form has to be filled up by the crew. Brit'Air has a flight analysis office, but up to now a study on the use of the HUD has never been performed.

The safety benefits of the HUD are obvious for traffic detection in VMC (light aircraft or other transport aircraft). The danger usually comes for low speed traffic, also speed is limited to 250 knots below level 100 in order to reduce the differences of speed among the different aircraft types.
The benefits of the HUD are especially :

- the easiness and precision of the aircraft control
- the easy transition from IMC to VMC
- the natural increase of the head up time duration

The chief pilot has to know some specific traps :

- a bad brightness adjustment ;
- an excessive precision to follow the flight director, which may be tiring ;
- an over focalisation on the HUD without checking its functioning (cross checks and global situational awareness are always required).

Possible improvements

The current symbology is satisfying, no modification is required.
The use of colours, the addition of a taxiway guidance or enhanced vision could be interesting features in the future.

Perspectives of use

The airline is currently satisfied with the HUD, which today is obviously not the main issue in the context of competition.

The older aircraft won't be equipped with a HUD because of the associated cost, but the new CRJ 700 will be equipped.

4.3. Comparative analysis of the exiting symbologies

4.3.1. Methodology

A systematic comparison of the symbologies has be carried out considering the following flight phases and manoeuvres because of their relevance for safety :
- 3 flight phases : cat. III approaches, take-off roll and roll out.
- 2 transitions : go-around and take-off rotation,
- presentation of information relative to special situations and features : unusual situations, out-of-view symbologies, wind shear, TCAS and GPWS.

The comparison is focused on the symbologies described in chapter 4.2, shared into two groups depending on their main concept of use :
- symbologies dedicated to manual control (manual HUD) : the Baé VGS and the Flight Dynamics HGS of the B 737NG, plus the Flight Dynamics HGS of the CRJ,
- symbologies designed for the monitoring of the autopilot (monitoring and hybrid HUD) : the Sextant HFDS of the B737 and MD82, and the Sextant HUD of the A320.

The technical documentation used for these comparison is referenced in Appendix 12.

4.3.2. Category III approach

The capability to proceed to low visibility approaches is one of the main reasons to equip the civil transport aircraft with a HUD.

The Appendix 14 presents :
a) the 6 different cat. III approach symbologies used for comparison
b) the synthesis of their comparison
c) a table identifying which symbol is used on all the symbologies (the common basis) and the symbols which are specific to one symbology.

The comparison clearly shows the noticeable differences between the two groups of symbologies:
- The HUD from the manual concept are designed as primary flight instruments, presenting most of the head-down piloting and navigation information. The common basis is widely shared, which indicates a consensus between the manufacturers and/or certification teams concerning the necessary symbols. The differences are limited to some details, which constitute a kind of trademark of each manufacturer (shape of the velocity vector and runway symbol, indication of side slip and angle of attack, value of the DH,…).
- The HUD form the hybrid or monitoring concepts only presnt the very necessary information for the task. The symbology makes use of the conformal, intuitive symbols to facilitate the monitoring of the aircraft trajectory. The common basis is more limited than for the manual concept, which reveals the difference of generation between the two symbologies compared, and the evolution of the hybrid concept.

4.3.3. Take-off roll and landing roll-out

The Appendix 15 presents the result of the comparison of the 6 symbologies for these two ground phases.
The main differences between the HUD appear to be linked primarily with the concept of use.
The symbologies presented on the hybrid and monitoring concept HUD are limited to essential information.
The symbologies of the manual concept HUD are similar, the differences are limited to the choice to display some information items such as DME or vertical speed even on ground.

4.3.4. Transitions : go around and rotation

The Appendix 16 is the result of the comparison of the changes happening in the symbologies during these transition manoeuvres.

Only the symbols changing on at least one of the compared symbologie are mentioned.
The A320 HUD doesn't appear in the tables, because the use of this HUD is not allowed during these manoeuvres, which have to be performed head down.

The tables show that different solutions are adopted by the manufacturers to address these delicate transition manoeuvres :

Generally speaking, these manoeuvres impose a change in the way to operate. When using a HUD, the change may concern :
- the control information (from a flight path angle to a pitch angle) ;
- the piloting mode (from manual to automatic or the opposite).

Some delicate points have been identified (and solved most often) :
- the lack of precision of one indication (e.g. the pitch scale of the A320 HUD implied the restrictions of used cited above);
- the lack of cues to incite the pilot to use the pitch reference instead of the flight path reference (e.g. the special pitch scale of the HFDS was developed to solve this issue) ;
- a default in the symbol dynamics (e.g. the velocity vector lag on the Transall HUD) ;
- the change of guidance law used by the flight director (e.g. falre guidance on the HGS).

4.3.5. Special functions

The Appendix 17 presents, for each HUD, the solutions used for 5 types of special situations :
- unusual situations
- out-of-filed symbologies (e.g. if case of strong cross wind)
- windshear
- TCAS advisories
- GPWS warning.

All the HUD form the manual concept provide some information for these special situations (except the TCAS and GPWS not displayed on the CRJ HGS). The solutions are relatively similar, which reveal the current consensus on these issues.
One can describe the interesting following features :
- The unusual situation symbologies consist of a light symbology similar to an artificial horizon, completed by a compressed pitch scale and a special chevron in the direction of the sky.
- The out of filed symbols are presented as dotted symbols in order to show that they're no longer conformal (e.g. horizon line and velocity vector).

The monitoring and hybrid HUD only address the out-of-field situation, with dotted symbols as is done on the manual HUD.

4.3.6. Synthesis of the comparisons

The various comparison show that a common agreement currently exist in facts for the basis symbology, depending on its concept of use, manual or monitoring/hybrid.

Some differences still exist between the manufacturers to solve some issues and delicate situations (transition manoeuvres,…).

Special features are provided o the more recent HUD to display advanced information (TCAS, GPWS).

From a methodological point view, the comparisons show that an approach simply based on a symbology specification is not adapted and that it is necessary to proceed to a more precise analysis taking into account the aircraft technical environment of the symbology (concept of use, head down compatibility).

A consensus appears for the design of the basic symbology, depending of its concept of use, while some differences still exist between the symbologies for transitions and special functions. The constitution of a symbology closely depends on its context of use, which limits the potential relevance of a symbology specification out of its context.

4.4. Comparison of the existing symbologies with the regulatory requirements

4.4.1. Constitution of the symbologies and the explicit requirements of the regulation

The table in Appendix 18 presents a synthesis of the comparison of the existing HUD with the regulation, for cat. III operations.

The comparison shows that the existing symbologies naturally provide more information than what is explicitly required by the regulation : the regulation only guarantees a minimum standard and imposes some limits for safety, but doesn't constitute a design guide.

The comparison extended to the other flight phases leads to the same conclusion : a gap exists between the regulatory requirements and what is actually displayed on the HUD ; this gap is of course generally not a negative indicator.

It also reveals the part left in the decision to the certification expert. For instance, the vertical velocity is not always displayed explicitly in the HUD,
while it is required explicitly by the regulation ; nevertheless, it can be deduced from the airspeed and from flight path angle indication, which was probably agreed as satisfying by the experts for the intended use. This is also the case for wind or side slip angle information.

4.4.2. Actual use and functions available

Behind the expected gap between the regulatory requirmenets and the existing symbologies, the information collected on the actual use of the HUD in the airlines and the technical documentation from the HUD manufacturers reveal a gap between the actual use and the functionalities of a HUD.

For instance, it is worth to note the gap sometimes existing for the manual HUD, between the prescribed use and the actual use, usually for economical reasons. These HUD are usually designed and certified for low visibility operations under manual control, while their actual use is more general : they are used for VMC operations and for AP monitoring on aircraft equipped with autoland (SAS, Delta or Alaska Airlines, EasyJet,..). However, the prescribed use is progressively extended, either for the retrofit of old aircraft or even new aircraft not equipped with autoland (B 727, B 727 NG at SouthWest et American Airlines).

Some gaps also appear between the technical documentation of HUD and its current certification. Some pilot guides mention some modes which are not yet certified, also available on the equipment. These gaps are progressively reduced, as the certification is usually progressively extended to the less critical operations.

For instance, the HUD of the manual concept provide numerous modes in order to cover all possible flight phases, which first are not certified. The control of their use only depends on the restrictions of use published in the technical documentation.

Some other restrictions of use are also formulated by the airline itself, as a result of the experience and difficulties collected during the operations.

These gaps between the available functionalities of the equipment, the prescribed use and the actual use of a HUD are depicted by Figure 7. They constitute some possible weaknesses which require special attention, and should be addressed at the instruction level and controlled by experience feedback systems. An other way of action is to limit the possible functionalities to be offered by an equipment.

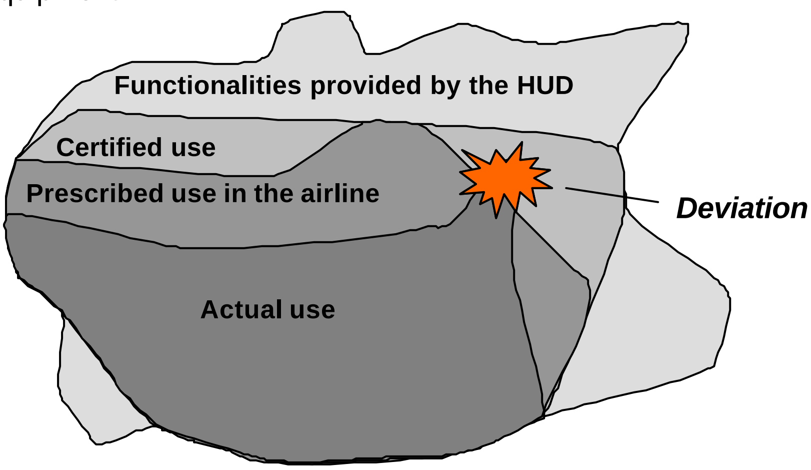


Figure 7 : The gaps between the available, the prescribed and the actual uses.

As a conclusion, the constitution of a symbology results of a compromise between the different needs of :

- the regulation authority : guarantee some minimum standards ;
- the designer : concept of use, commercial image and benefits, cost of the certification ;
- the certification team : insure a global performance and safety level within the intended use ;
- the airline : operational benefits, economically measurable ;
- the crew : insure an efficient strategy given his instruction, background and experience ; safety and comfort of the passengers.

4.5. Synthesis on the actual use of the HUD

4.5.1. Some suspected weaknesses…

The review of the existing HUD and the opinion collected among the users indicate the influence of the concept of use, which is a primary determinant of the constitution of a symbology.

Each concept of use implies a compromise between the information required and the limitations specific to the head-up display.

More precisely, the following weaknesses have been identified for the two main concepts :

For the hybrid or monitoring concept :

- Over confidence resulting in a difficulty to react in case of an non frequent event (AP failure,..)
- Delicate transition from automatic to manual control (go around or flare)
- Difficulty to detect the abnormal slow evolutions (symbols fixed or subjects to deriving)

For the manual concept :

- Over focalisation on the flight director, resulting in long reaction times in case of changes in the a/c state or warnings;
- Cluttered symbology (cognitively) masking the external vision ;
- Delicate transition from flight path piloting reference to pitch angle (during flare or go around);
- Bad dynamic behaviour of the symbology (useless precision or design of the animation law).

4.5.2. … but the users' opinion is generally positive

In facts, the experience feedback sources and users' opinion provide very few negative indication concerning safety. Also the available objective information sources are weak, the global consensus is that the use of the HUD is beneficial for safety.

This opinion is shared not only for low visibility approaches subjects of the certification, but also for visual operations, because of the gains in easiness and precision of the aircraft control.

The delicate points listed above for the two concepts of use are generally well identified and subject to a special attention during crew training and qualification for the use of the HUD.

The comparative analysis of the existing symbologies shows a tendency to a uniformisation of the basic symbol set, and still in progress for the special situations and for the more recent symbology features (warnings, windshear, GPWS, TCAS). A similar uniformisation exists for head down instruments : it is beneficial to ease the changes of qualification and to avoid the possible confusion between symbols.

However, the HUD is still a particular flight instrument, which modifies the share of tasks in the cockpit and which requires a regular practice.

Last, the confrontation of the actual operational use of a HUD with its use prescribed by the certificator or by the operator sometimes reveals some gaps, which are fortunately progressively reduced when the certification is extended to all the operations for which the HUD is intended to be used.

5. Methods and evaluation criteria through the HUD literature

The last step of this study of potential issues in the use of the HUD concerns the numerous research works addressing either the design or the use of a HUD.

This review is also useful in order to recommend some evaluation methods and criteria for their possible application to a certification process.

The review is organised with the following topics :
- the issues addressed in the literature
- the experimental means
- the evaluation criteria and parameters
- the scenario and experimental variables
- the choice of the subjects
- the methodology used for analysing the results

5.1. The issues addressed in the literature

The HUD has been the subject of many research works for the last twenty years (Appendix 19); which don't have to be exhaustively read in order to identify the main current issues concerning the HUD.
Two aims closely match the objective of the present study :
- the research for possible weaknesses of the current HUD ;

- the possible consequences of the changes of the HUD themselves and of the global aeronautical environment on the use of the HUD.

5.1.1. Possible weaknesses of the current HUD

The various experimental investigations study the means to quantify the weaknesses and limitations of the HUD and how to avoid them. The main issues are :

- the share of attention between the HUD symbology and the external world (Boston & Braun, 1996 ; Foyle, McCann, Sanford & Schwirzke, 1993 ; McCann et al., 1993 ; Wickens, 1994),
- the conformal presentation of information, for instance for unusual situations recovery (Billingsley & Kuchar, 2001 ; Weinstein & Ercoline, 1991 ; Weinstein, Ercoline & Gillingham, 1992 ; Zenyuh, Reising, et al, 1987 ; Previc & Ercoline, 1999),
- the necessary exhaustivity of the information for the use of a HUD as a primary flight display (Weinstein & Ercoline, 1992 ; Weinstein, Ercoline & Gillingham, 1992),
- the clutter effects (May Ververs & Wickens, 1995 ; May Ververs & al., 1998) ;
- the efficiency of failure indications in the HUD (Ligett & al., 1993)
- the effects of symbology features on decision timing, for instance during the flare phase (Mulder et al., 2000).

5.1.2. Future trends

They primarily concern the changes in the future air traffic control procedures.
Some crew decision aids appear to be necessary and the HUD may be an efficient solution to display the new information items while allowing the external vision.

- The curved instrument approaches are typical applications : in this context the HUD combined with GPS information could be used as a flight instrument (Reising & al., 1995, 1998). Levy, Foyle, Mc Cann (1998), Snow & al. (1999) have compared several types of symbology to help the control of the 3D flight path, depending or not of the actual environment.
- The ground phases are also often considered, as the trafic density and runway complexity are increasing. 3D maps are presented in perspective with a superimposed guidance symbology (McCann & al., 1997).

5.2. Experimental means

The scientific investigations make use of different experimental protocols and means in order to highlight the factors relevant to their issue, from a simple computer screen to the Full Flight Simulator.

Some very rudimentary means are used to study the basic effects of HUD, such as attention allocation, clutter and decision making (McCann & al., 1993 ; Foyle, McCann, Sanford, Schwirzke, 1995 ; May Ververs & Wickens, 1995 ; May Ververs & al., 1998 ; Mulder & al., 2000) but also sometimes for laboratory situations on spatial perception (Levy, Foyle, Mc Cann. 1998 ; McCann & al., 1997). In this case, a work station is used to display the HUD symbology and to figure the external world at the same time.

The most representative environments are fixed based flight simulators providing the flight and navigation information and communication with other actors outside the cockpit, although the actual activity of the pilot is seldom described (Reising et al, 1995, 1998 ; Billingsley, Kuchar, 2001 ; Weinstein et al., 1994 ; Ligett et al., 1993 ; Zenyuh et al. 1987 ; Snow et al., 1999). The level of realism of the HUD remains low, as the HUD is generally simulated as superimposed on the synthetic image (e.g. not collimated). These quite sophisticated experiments are used to assess the difficulties of the operator in situations requiring a global situational awareness, such as unusual situations recovering, 3D guidance aids, or use of the HUD as a primary flight instrument.

It has to be mentioned also that some authors use a transfer of the application context in order to avoid the need of specialist subjects. For instance, Boston & Braun (1996) have studied the share of attention when using a HUD by means of a marine navigation simulator easily controlled by the students involved in the study.

5.3. Evaluation criteria and parameters

Two types of criteria are used in the research literature :
- objective criteria recorded in real time ;
- subjective criteria collected after the experiment and implying an auto evaluation of the operator of his/her activity.

The most frequently used objective criteria are :
- the deviation from prescribed flight parameters : trajectory, altitude, speed (Reising & al., 1995 ; Reising & al, 1998 ; Weinstein & al., 1994 ; Levy, Foyle, Mc Cann. 1998 ; Zenyuh & al. 1987 ; McCann & al., 1997 ; Snow & al. 1999)
- the necessary time to perform a manoeuvre (Billingsley, Kuchar, 2001 ; Boston, Braun, 1996 ; Zenyuh & al. 1987),
- the failures to perform the task (McCann & al., 1997),
- the detection time of a critical event (May Ververs & Wickens, 1995 ; May Ververs & al., 1998),
- the identification time of a failure and identification errors (Ligett & al., 1993 ; McCann & al., 1993).

The main subjective criteria are :
- questionnaires (Reising & al. 1995, 1998 ; Boston, Braun, 1996)
- half directed interviews (Snow & al., 1999)
- auto evaluation scales, such as the Cooper-Harper, the SA-SWORD for the assessment of the situational awareness (Weinstein & al., 1994 ; Snow & al., 1999)

Several criteria are available ; they have to be selected and combined depending on the research objective and on the possibilities offered by the experimental means. The two types of criteria are complementary : they should be associated to highlight the differences of performance between two situations (e.g., two symbologies) and to analyse the mechanisms implied during the activity.
None of the author makes use of more heavy methodologies such as activity collection and analysis based on actual activity recording.

5.4. Scenarios and variables

The scenarios used for research are various by their duration, the flight phase, the occurring events and the task prescribed to the operator, which makes them more or less representative of the actual flight conditions.
Nevertheless, most scenarios are quite far from reality because of the few interfering tasks that they involve.

The preferred flight phase is this approach phase (Reising & al., 1995, 1998 ; Levy, Foyle, Mc Cann. 1998 ; Snow & al., 1999 ; Liggett & al. 1993 ; McCann & al., 1993 ; May Ververs, Wickens, 1995), sometimes using the automatic approach mode when the manual control by the pilot is not the subject of the study (Mulder & al., 2000). The experiment is even sometimes limited to the few sconds preceding the touch down (Wickens, 1994).

The experiments of a long duration are less frequent, whether they concern the cruise phase (Foyle & al., 1993 ; Wickens, 1994 ; May Ververs & al., 1998) or even several flight phases (Billingsley, Kuchar, 2001 ; Weinstein et al., 1994).

Two examples of realistic scenarios have been noticed in the literature :
- one concerns an exhaustive study of the different flight phases and addresses the changes of attention and activity during the flight (Zenyuh & al., 1987) ; it consists of a 90 minutes mission

of a fighter aircraft to evaluate the efficiency of a HUD to recover from unusual situations, the pilot having to comply with the published procedures ;

- the other concerns a low visibility navigation on Chicago airport field, among 24 possible navigation schemas, from the parking place to the take off point (McCann & al., 1997). The mean distance is about 2 nautical miles and the duration about 7 minutes.

Among the experimental variables, except different symbologies, the experiments often make use of various visibility conditions (Reising & al, 1998 ; Snow & al., 1999 ; May Ververs, Wickens, 1995) or several levels of task difficulty (Billingsley, Kuchar, 2001).
Some events are introduced to interfere with the nominal activity : they may be meteorological, such as wind gradients (Reising & al., 1995, 1998 ; Foyle & al., 1998 ; Snow & al., 1999), emergency cases (Reising & al., 1995, 1998 ; Boston, Braun 1996 ; Wickens, 1994 ; Snow & al., 1999 ; Liggett & al., 1993), or a sudden unusual situation (Foyle & al., 1998 ; Weinstein & al., 1994 ; Zenyuh & al., 1987).

The production scenarios are usually preceding by a training phase of a sufficient duration in order to stabilise the operators' performance and to insure that the changes of performance can actually been related with the experimental variables. Of course, the time duration needed depends on the task complexity, which includes the level of realism of the simulation environment.

5.5. Choice of the subjects

The number of human subjects chosen for one experiment is generally relatively small (usually from 10 to 20). Each subject has to perform all the experimental scenarios after the training period. Generally, the number of subjects is higher when composed of non specialists (such as students), rather than pilots (the maximum number is 60 in Boston, Braun, 1996).
When pilots are involved, they generally have a long aeronautical expertise (typically above 1000 flight hours) but a much more reduced experience of the use of a HUD. The pilots are generally involved when the task is closely dependant of the aeronautical skills (curved approaches, unusual attitude recovery, information needed for use of the HUD as a PFD, clutter effects on external traffic detection,..).

5.6. Methodology used for results analysis

The objective criteria collected during the experiments are usually subject to a variance analysis, assuming that the different scenario variables are independent variables. The trends are sometimes difficult to establish due to the small number of subjects and runs.
The subjective data, such as individual responses to a questionnaire, are then analysed. Their synthesis is often the last chance to highlight the possible beneficial effects of a symbology for the operator.

As a conclusion, the research laboratories studying the current or future difficulties related to the use of the HUD usually develop relatively various experiments ; these experiments are designed for the purpose of the research issue, sometimes using an experimental environment quite far from the actual aeronautical context in order to facilitate the experiment.
However, for the needs of certification, the experimental environment, the tasks and the occurring events appear to be too simplistic to correctly take into account the interactions between the components of the actual task. So the usual laboratory experiment doesn't appear as a potential basis to elaborate a methodology for the purposes of certification. Nevertheless, the results of the research experiments still have to be taken into account in the certification process and the philosophy behind the experimental approach is also adapted for certification.

6. Recommendations for the evaluation methodology

The HUD evaluation is historically paradoxical because the first HUD products have been certified on the basis of a regulation which was actually far behind the proposed products. In facts, the larger part of the conceptual and technological issues have been addressed well before the regulation basis –although more reduced then the current one- could be established.

The question of HUD evaluation is still open, because of the current extension of the concepts of use and because of the emerging interactions with the new systems. These new issues are likely to increase the complexity of the analysis during the certification process. The complexity results of the exploration by the manufacturers or by the users of the existing regulatory margins, of new procedures (e.g. curved approaches) and of possible functions of the newer cockpit equipment (GPWS, TCAS, EVS,..). The HUD is no longer a simple display of piloting information dedicated to a single flight phase : its use is extended ; more functions are available and the potential traps and weaknesses could become more difficult to identify.

This new context should direct the review of the existing HUD regulation and the recommendations for their evolution. in other words, it is necessary to prepare the regulation basis for more complex certifications.

The previous syntheses concerning the existing regulations, the actual use of the HUD and the research literature on the subject may be used as a basis to establish some preliminary recommendations to guide the coming evaluations.

These recommendations are based on a discussion of the three following questions :
- Does the actual use of the HUD reveal a need for a change of the certification process ?
- Do the research experiments suggest some possible improvement points (results, methodology) which could be introduced in the existing regulation ?
- Could the current regulation be arranged in order to make its use more easy and clear ?

6.1. Does the actual use of the HUD reveal a need for a change of the certification process ?

The preceding chapters of this report have already shown the very small number of facts which could reveal a possible insufficiency of the HUD design and certification process. So the immediate answer to this question is negative.
However, it should be noted that the rate of HUD equipped aircraft is still low, and that the proportion of flights where the use of the HUD is mandatory is even lower : the lack of negative indicators has to be related to this limited operational practice.

A first recommendation may be proposed concerning this lack of operational data :
The experience feedback is actually very weak, whether about the actual use of the HUD (performance, frequency,…) or about its specificities. An experience feedback could be structured on the basis of a continuous monitoring as advised in the JAR OPS Temporary Guidance Leaflet n°20 concerning all-weather operations with HUD systems, in its two paragraphs :
- (2.3.2.) report of the total number of approaches to cat. II or III minima and report of unsatisfactory approaches ;
- (2.3.3.) an operator should establish a procedure to monitor the performance of the HUD guidance system of each aeroplane.

Some points could be subject to a more specific analysis and investigation on the performance of the symbology; For instance, the transition phases, the unusual situations and strong turbulence conditions implying a fast dynamic and deep changes in the symbology could be specifically addressed, as they are not currently directly taken into account in the existing regulation.

An other practical point has appeared through years of HUD usage and has been pointed out several times in this report: some very similar regulations have produced quite different symbology designs. In fact, the differences between the operational contexts, the types of aircraft, and the

aeronautical cultural environment have powerful effects on the constitution of an adequate symbology.
The question is now to be sure that the different philosophies concerning HUD symbology will adequately fit the possible coming changes of their various contexts of use.

So, an aim is to develop methods to evaluate the symbologies within the complexity of the actual situations, and especially the situations which are not frequent but potentially difficult for the use of the HUD (transitions, avoidance, bad meteorological conditions, unusual situations,..).

This recommendation leads to the next question related to the methodologies developed for research purposes.

6.2. Do the research experiments suggest some possible improvement points which could be introduced in the existing regulation ?

The most specific point resulting from the analysis of experimental research works about HUD symbology concerns the methodology used.
However, the direct transposition of these methodologies (from the studies reviewed in chapter 5) to the certification process doesn't seem directly feasible, because they do not consider the operational environment nor the certification constraints :

- The experimental studies (for the last 10 years) generally don't use an actual HUD ;
- They do not address the complexity of the use of the HUD in the operational context ;
- The dynamic aspects of the HUD use (among the crew members, or with the other available information sources or systems) are usually not explored either.

Although the experimental studies do not satisfy the need for methodological developments for certification, they are of course very useful to open new directions for the extension of the use of the HUD, for the need of the manufacturers. This is indeed the primary goal of most research studies.

In terms of methodology, the research works show **the potential benefits of the combination of objective and subjective evaluation criteria**.
Currently, the method used for certification is of a quantitative nature and makes use of objective performance criteria such as the position of the impact point, speed deviations,...
The purely quantitative criteria could be efficiently correlated with qualitative criteria. For instance, the mean deviation is only significant of the level of control in the simple experimental context but do not allow any conclusion concerning the robustness of the control in the actual conditions, which may reveal the limits of the system under evaluation.

On the other hand, a detailed human factors evaluation can hardly been proposed in the frame of a certification process, because of its cost, complexity and duration, and because of the large number of subjects (airline an test pilots) which should be required.
Two ways could help to get round this constraint :

- a more deep analysis of the human factors related to the evaluation to be performed, which should be conducted at the design stage by the manufacturer ;
- an increased human factors know-how of the certification experts, in order for them to be able to appreciate the manufacturer's analysis and to enrich the quantitative results by their own investigations.

The resulting recommendation is to provide the certification experts with some "suspicion points" concerning the human factors data of HUD evaluation.
This approach using suspicion points is similar to the general certification approach of a particular technical equipment which first addresses the conditions of use known for their difficulty or for their specificity.

The spatial representation elaborated by the pilot through the HUD, the attention mechanisms or the time needed to analyse an unusual situation are all examples of suspicion points specific to the HUD.

6.3. Could the current regulation be arranged in order to make its use more easy and clear ?

The study of the existing JAR regulation leads to two recommendations concerning HUD evaluation :

- **The data relevant to the evaluation are disseminated among a large set of references, which could be arranged with a more coherent structure**. This structure wouldn't replace the existing documents but would help to regroup them.
- The current regulation is primarily written for the needs of the manufacturer. **It seems necessary to build a complementary document which should be primarily concerned with the evaluation methodology** and so, structured according to the needs of the certification experts.

Let's detail these two recommendations :

6.3.1. Regroup the disseminated regulations

The main regulatory elements are provided in JAR 25, AMJ 25-11, JAR HUD 901, 902 and 903. Some of these elements specifically concern the HUD, while some are originally related to the electronic flight instruments.
The equipment must be designed according to the general principles enunciated in JAR 25.1309. The work load is mentioned in JAR HUD 903 and takes the HUD specificities into account (eye strain, rigid head position, excessive mental concentration), but it refers to texts which are somewhat incomplete about this issue (JAR 25.1523).
An other example of text dissemination is reported in the « Human factors aspects of flight deck » JAA interim policy, which considers that the human factors aspects of the flight deck changes are not adequately addressed by JAR 25 existing requirements. The novel features introduced in the cockpit justify the need for a special condition under the terms of JAR 21.16, addressing the performance, capability and limitations of the flight crew, including the effects of crew errors.

An illustration of the attempt to synthesise the various aspects of the HUD is provided by SAE ARP 5288 "Transport category airplane, Head Up Display systems", which reassemble HUD specific definitions and concepts, an analysis of the failures, numerous data on the HUD installation and optical characteristics, and some verification considerations. It should be noticed that this document refers to FAA Advisory Circular 25-11 "Electronic Instrument Systems" which is similar to JAA AMJ 25-11.

6.3.2. A complementary document concerning the evaluation methodology

Up to now, there is now text explicitly describing the evaluation methodology for the need of the certification expert. In particular, there is no "flight test guide" published for the HUD. The existing documents indicate the characteristics and objectives to be reached during the HUD design phase.

The indications concerning the methodology are quite limited. For instance, the performance demonstration expected under JAR HUD 901 is based on the correct achievement of at least 1000 simulated approaches plus 100 approaches in real flight. The approaches have to be performed by at least 10 pilots including different backgrounds and experience. They should have current licences and should be given training in the use of the HUD similar to that given to line pilots. There is no mention of specific scenarios, which could help exploring special situations, such as strong turbulence, transitions including go-around, or unusual attitude.

The lack of a methodological guide for the certification process also constitutes an obstacle for the conservation and the comparison of the knowledge acquired and of the results.
The nature of the approach by itself reveals this difficulty : the certification experts have to appreciate that the equipment satisfies with the "minimum standards for safety". This minimum can not be described precisely for every equipment : the certification expert still has to build his/her own appreciation. The certification approach is fundamentally based on the experience and so it remains empirical.
The JAR HUD 901, AWO H307 « HUD characteristics » is typical of this situation. Three topics are addressed : Equipment installation, Display presentation, and Display symbology, for which only general guidance objectives are provided, without specifying any evaluation criteria or methodology.
The methodology definitely appears like the means to stabilise and share the know-how and the results obtained during a certification campaign.

The SAE ARP 5288 already cited provides some interesting considerations for the need of evaluation (also very similar to FAA AC 25-11 and JAA AMJ 25-11) :

The general approach of human factors :

> *Humans are very adaptable, but unfortunately for the display evaluation process, they adapt at varying rates with varying degrees of effectiveness and mental processing compensation. Thus, what some pilots might find acceptable and approvable, others would reject as being unusable and unsafe. Aeroplane displays must be effective when used by pilots who cover the entire spectrum of variability. Relying on a requirement of "train to proficiency" may be unenforceable, economically impracticable, or unachievable by some pilots without excessive mental workload as compensation.*

The topics addressed are the following : *colour, symbology, coding, clutter, dimensionality, and attention-getting requirements; display visual characteristics; failure modes; information display and formatting; specific integrated display and mode considerations, including maps, propulsion parameters, warning, advisory, check list procedures and status displays*.

It also specifies that the certification programme should include a sufficient number of simulation and flight test, involving a representative pilots population in order to guarantee :
- *Reasonable training times and learning curves;*
- *Usability in an operational environment;*
- *Acceptable interpretation error rates equivalent to or less than conventional displays;*
- *Proper integration with other equipment that uses electronic display functions;*
- *Acceptability of all failure modes not shown to be Extremely Improbable; and*
- *Compatibility with other displays and controls.*

The following content could be proposed for a methodological guide (some already exist in the regulation, some are specific) :

• Reminder of the existing regulation concerning the use and evaluation of the HUD

• Reminder of HUD specific definitions and concepts

• Reminder on HUD human factors issues :

    Attention effects in the use of a HUD

    Spatial représentation through the HUD

    Specificities of the HUD piloting (benefits and traps ; guidance limitations ; lag effects ; lighting conditions,..)

Cockpit interactions with a HUD

• Methodology for the evaluation of a HUD symbology

Task analysis

Experimentation
Choice of the scenario
Choice of the subjects : number, background and experience (including line pilots)
Exploration of the various intended uses and different modes (manual, automatic,..)

Available methods for the human factors evaluation of the use of the HUD :
Cooper Harper rating scale, questionnaire, semi directed interviews, in flight observation
Analysis of performance measures : deviation from target values or performance objectives (failure detection, decision time,…)

7. Conclusion

The analysis of the use of the HUD shows a paradox : it occupies a particular place on the flight deck, located in the centre also relatively seldom used.

Actually, the highly automated aircraft do not depend so much on the HUD as long as they operate on well equipped airports ; less automated aircraft have to use it but only in still exceptional conditions. So the actual use of the HUD evolves from the high tech information display essentially providing comfort to the user, to the necessary tool which use is limited to rarely occurring situations.

The distribution of the HUD is also quite punctual and varying : some fleet are largely equipped, some only partially, some business aircraft fleet could be equipped rapidly, while in other segments, the HUD is almost non existent.

The main conclusions of the present study also illustrate different aspects of the HUD paradox :

- The review of the existing regulation reveals a contrasted inventory : the organisation of the FAA and JAA regulatory texts applicable to the HUD is complex and involves several dimensions. The concept of use (manual,, monitoring or hybrid HUD, primary or additional flight instrument) primarily determines the applicable requirements, and so it could guide a possible re arrangement of the texts.
- The recent JAR HUDS regulation appear clearer and better organised than the corresponding FAA regulation ; they address the HUD issues in terms of functional requirements, which seems to be a better adapted rationale than trying to establish a standard symbology specification independent from the intended context of use.
- The draft FAA and SAE documents aim to compensate for the lack of a general HUD document in the American regulation : these texts also use the functional approach of the existing JAA documents, but they provide more details and they address emerging concepts such as EVS. They could constitute a basis to guide the next changes of the JAA regulation.
- The differences between the JAA and FAA regulation concerning the HUD symbology are not actually significant ; they are more indicative of different text levels, than of differing approaches of the design of a HUD symbology.
- Some more significant differences appear at the level of regulation interpretation by the certification experts. These differences are linked to the different conceptions of the use of a HUD, and further, of the role of the pilot, among the experts.

- The certification process is based on the existing regulations, but moreover, on the various technical (aircraft compatibility, intended use) and cultural dimensions (certification experts' background, users' habits). The certification methodology is focused on performance : the certification constraints limit the possible application of evaluation methods specifically addressing the subjective human factors considerations provided in the regulation.
- The analysis of the existing symbologies allows to distinguish three types of HUD symbologies, directly related to the intended concept of use : monitoring, hybrid or manual. A common basis of the symbol set can be identified and constitutes a stabilised consensus among the manufacturers, for the usual flight phases. Some more original solutions do exist for transition manoeuvres (go-around, flare and rotation) and for particular functions provided by the new systems (GPWS, TCAS).
- The confrontation of the existing symbologies with the current regulation reveals a gap : the symbologies are actually 'in advance' compared to the specific requirements of the regulation : they provide more capabilities than required, and they reveal the manufacturers know-how to solve specific problems which are not addressed in the regulation.
- A less expected gap is sometimes seen, between the very large domain of the possible uses of a HUD, proposed by the designer and actually available on board, and the certified domain of use, which is usually limited to the most critical flight phases (approaches) and specified by the operator. This gap is linked to the cost and time needed to extend the certification process to all the possible uses provided by the recent HUD systems.
- The operational sources provide very few experience feedback on the actual use of the HUD : they do not reveal any significant safety issue directly linked to the HUD. Whatever is the concept of use, the interviewed HUD users are satisfied with the equipment and claim its benefits in terms of ease and accuracy of the aircraft control. However, they recognise the need for a specific training and regular practice for the safe use of the HUD.

As a conclusion, the analysis and interviews conducted during the present study clearly show that the constitution of a HUD symbology results from a compromise between technical constraints, operational needs, differing conceptions of the use of the HUD and economical considerations, which can hardly been addressed in the regulation.

A fruitful literature has already been published about the experimental research works addressing many HUD specific issues : information conformity, attention and clutter effects,... These work have resulted into the current consensus on the basic symbology ; they do not provide a directly useful methodology for application to the certification process.

The lack of negative safety indicators and the existing consensus on the constitution of the basic symbology limits the potential interest of a test program focused on the performance of one particular symbology within the current aeronautical environment, especially if the experimental means is not representative of the actual context of use.

A test program used as an illustration of an evaluation methodology for the need of certification seems to be more adequate if the present study is to be followed by a second phase, depending on the availability of an adapted experimental subject. The application context could concern one of the new concepts envisaged for the future evolutions of the aeronautical environment, in order to contribute to the necessary thought concerning the regulation needed to accompany these emerging concepts.

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Appendix 1 : Contract references

[1] DGAC/SFACT
Recherche pré normative sur la sécurité de l'aviation civile
Programme fonctionnel DGAC/SFACT (7 octobre 1998).

[2] DGAC/SFACT
Notification du marché n°99.50.074.00.227.75.0. Réalisation de travaux en vue de maintenir la sécurité du transport aérien à un niveau acceptable. Lot 3 : symbologie HUD.
Contrat N°21320 – SFACT/AEF du 23 juin 2000, reçu le 03 juillet 2000

[3] DGAC/SFACT
Règlement particulier de consultation (RPC)
N° 98/01 du 23 novembre 1998.

[4] DGAC/SFACT
Cahier des clauses administratives particulières (CCAP)
N° 98/01/C du 24 novembre 1998.

[5] Le Blaye P.
Symbologie des collimateurs tête haute (HUD)
Proposition technique et financière ONERA DCSD 7009.06 (février 1999)

Appendix 2 : Abbreviations

AC	Advisory Circular
ACJ	Advisory Circular, Joint
ADI	Attitude Director Indicator
AGL	Above Ground Level
AMJ	Advisory Material Joint
ARP	Aerospace Recommended Practice (SAE)
AS	Aerospace Standard (SAE)
ASRS	Aviation Safety Reporting System
AWO	All Weather Operations
BASEAC	BASe d'Accident du CERMA
CDB	Commandant De Bord
CEV	Centre d’Essais en Vol
CRI	Certification Review Item
CSERIAC	Crew System Ergonomics Information Analysis Center
DCSD	Département Commande des Systèmes et Dynamique du vol
DGAC	Direction Générale de l’Aviation Civile
DH	Decision Height
DME	Distance Measuring Equipment
EADI	Electronic Attitude Director Indicator
EFIS	Electronic Flight Instrument System
EGPWS	Enhanced Ground Proximity Warning System
EHSI	Electronic Horizontal Situation Indicator
EVS	Enhanced Vision System
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FCL	Flight Crew Licensing
FHA	Functional Hazard Assesment
FMC	Flight Management Computer
FMS	Flight Management System
HFDS	Head-up Flight Display System (® Sextant)
HGS	Head-up Guidance System (® Flight Dynamics)
HQRS	Handling Qualities Rating Scale
HSI	Horizontal Situation Indicator
HUD	Head Up Display
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMASSA	Institut de Médecine Aérospatiale du Service de Santé des Armées
IMC	Instrument Meteorological Conditions
JAA	Joint Aviation Authorities
JAR	Joint Aviation Requirements
LVP	Low Visibility Procedure
MEL	Minimum Equipment List

NPA	Notice of Proposed Amendment
PA	Pilote Automatique
PF	Pilot Flying
PFD	Primary Flight Display
PNF	Pilot Not Flying
POC	Proof of Concept
RTCA	Radio Technical Commission for Aeronautics
SAE	Society of Automotive Engineers
SFACT	Service de la Formation Aéronautique et du Contrôle Technique
SOAR	State Of the Art Report
SOP	Standard Operation Procedure
SVS	Synthetic Vision System
TCAS	Traffic Collision Avoidance System
TSO	Technical Standard Orders
VFR	Visual Flight Rules
VGS	Visual Guidance System (® BAe Systems)
VMC	Visual Meteorological Conditions
VORTEX	Visualisation Objective des ReTour d'Expérience

Appendix 3 : HUD key words

The key words below are significant of common HUD issues. The related definitions and concepts are addressed in several regulation documents (e.g. JAR HUD 903, SAE ARP 5288), in the scientific literature or in the reference books (e.g. Newman, 1995 or Weintraub & Ensing, 1992)

Collimation at infinity

Conformity

Head-down compatibility

Clutter

Concept of use : manual / monitoring / hybrid

Operation category I, II, III a and III b (JAR OPS 1E).

Fail passive landing system

Fail operational landing system

Fail operational hybrid system

Field of view

Mode confusion

Primary instrument

Unusual situation

Attentional tunneling / Cognitive capture

Instruction and training

Function criticality

Workload

Symbology
frame of reference
basic T
digital / analogue
shape / size / location
dynamics / latency / quickening
caging / hierarchy
masking

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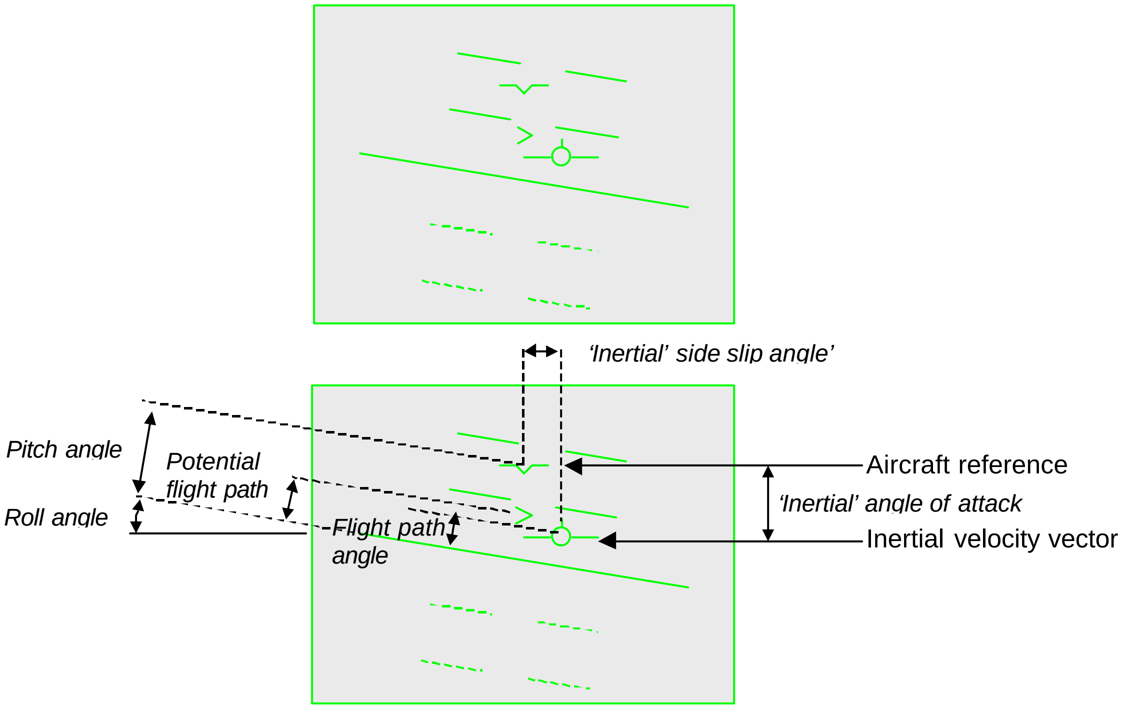
Appendix 4 : Description of the main HUD symbols

The symbologies of the modern HUD systems are built around a basic analogue and conformal symbol set, which, once completed with the digital values of altitude and airspeed, provide all necessary information for the pilot to control the aircraft.
This basic symbol set is already shared by all the manufacturers : this appendix presents this typical symbol set and briefly reminds the signification of the main symbols.



Aircraft reference symbol :

This symbol commonly referred to as the bore sight symbol represents the projected centreline of the aircraft. It is positioned at a fixed position on the display, unlike all other symbols which are placed around it.

Horizon line and pitch scale :

The horizon line represents the local horizontal plane. It is displayed relative to the aircraft reference symbol : the distance between the a/c reference symbol and the horizon line is equal to the pitch angle : the aircraft reference symbol is on the horizon when the pitch angle is equal to zero, and the inclination of the horizon is equal to the a/c roll angle.
The pitch scale is fixed to the horizon line. It is usually scaled in five degrees increments.
The horizon line and the pitch scale provide the pitch and roll attitude required as elements of the basic T.

Inertial velocity vector :

This symbol is a key feature of the head up display, as it directly represents the direction point of the aircraft. It provides an immediate indication of where the aircraft is going. The pilot can manoeuvre the aircraft and fly the flight path to the desired point, for instance, to the runway touch down point. If the velocity vector is above the horizon line, the aircraft is climbing.
The symbol is inertial derived, so the wind effects are included.
The angular distance between the aircraft reference symbol and the velocity vector provides an indication of the angle of attack and of side slip angle (plus wind effects).
NB : This symbol is now reproduced on the head down displays of some recent aircraft.

Potential flight path :

This symbol is another key feature of the modern HUD symbology, originated from French flight test engineers (MM. Klopfstein, Wanner,…).
The value of the potential flight path is significant of the instantaneous flight path acceleration.
It is derived from the aircraft total energy :

$$E = mgz + \frac{1}{2} m V^2$$

By analogy, the total aircraft height is defined as :

$$H = z + \frac{V^2}{2g}$$

The derivation is the total vertical speed :

$$W = \frac{dH}{dt} = Vz + \frac{V}{g}\frac{dV}{dt}$$

Using $Vz = V \sin \gamma$, the potential flight path angle can be defined by analogy by :

$$\sin \gamma t = \sin \gamma + \frac{1}{g}\frac{dV}{dt}$$

If the calculated sinus value is more than one, this means that the current thrust is enough to allow a continuous acceleration on a vertical flight path (the case with some modern fighters..).

The potential flight path chevron is conformally presented as a chevron positioned relative to the velocity vector.
If the chevron is above the velocity vector, the aircraft is accelerating.
If the chevron is positioned on the pitch scale at for instance, a 10° flight path angle, the aircraft is able to climb at a 10° flight path angle at the current speed.

The potential flight path can be used very effectively to control speed or flight path angle.
It is for instance a precious piloting aid to stabilise the approach, to pilot the aircraft on the back side of the polar, to climb over clouds or obstacles, e.g. in case of go-around or engine failure.

Other common symbols and digital values :

Airspeed and ground speed

Their values are usually displayed, as they are useful for the pilot to know respectively the current aircraft handling qualities and its current total energy (for instance in case of windshear).

Barometric altitude and radio height

Their knowledge is also essential, either for aircraft piloting and navigation.
The radio height is usually only displayed at low altitude (typically below 1500 feet), depending on the performance of the radio height sensor.

Vertical speed

The magnitude of the vertical speed can be estimated from the flight path angle combined with the ground speed, so it is not strictly necessary to display its digital value.
However, the exact knowledge of the vertical speed is often useful to follow the air traffic control instructions and some pilots are used to it : so the digital value is generally displayed in feet per minutes.

Speed deviation

The speed deviation from the current selected speed is often displayed as a speed error tape positioned on the 'wing' of the velocity vector. Its knowledge is especially useful, combined with the potential flight path chevron, to monitor the aircraft automatisms (e.g. autothrottle).

Appendix 5 : Review of the existing HUD regulations

JAA regulation

JAR 25 : Large Aeroplanes, AMJ 25-11 : Electronic Display Systems.
Change 14, 27 mai 1994.

JAR AWO : All Weather Operations
Change 2, 1st August 1996.

JAR HUDS 901 : Category 3 Operations with a Head Up Display
Issue 18, 11 avril 1994.

Some extracts :

JAR-AWO H307 : HUD characteristics : (c) Display symbology :

(i) Symbology design :

The designed symbol set (size and font) must be clear and uncluttered and enable easy assimilation of the displayed information. It must have no features which might lead to confusion or to an error by the pilot.

The display format must contain features minimising the possibility of pilot fixation on the symbology when the aircraft is near the ground.

There must be clear and unambiguous indication to the pilot of pitch and bank. If non-conformal positioning of normally conformal elements occurs (e.g. horizon line and flight path vector), this must be clearly indicated [not by a message].

(ii) Symbology hierarchy

A symbology hierarchy must be established such that higher priority symbology clearly and unambiguously overwrites lower priority symbology.

(iii) Compatibility with head down instruments

The HUD symbology must be sufficiently compatible with normal flight instruments to prevent misinterpretation or difficulty in transition between the two types of display.

(iv) Outside world view

(…) If an artificial runway or other external ground references are provided they must correlate with the real world as seen by the pilot.

JAR-AWO H315 : Decision height determination

(…) arrival at the decision height must be positively annunciated on the HUD.

JAR-AWO H316 : Go around

The HUD must provide sufficient information to permit the pilot to initiate and stabilise a go-around manoeuvre during the approach and flare without reverting to other displays.

The approach information must be removed on selection of go-around unless it is shown that its presence does not interfere with the go-around information.

JAR-AWO H323 : Automatic throttle control

An automatic throttle control system must be installed unless it can be shown that :

aeroplane speed can be controlled without an excessive workload

the touchdown performance limit are achieved

(…) The mode in which the auto throttle is operating must appear in the HUD.

JAR-AWO H351 : Mode selection and switching

A positive and continuous indication must be given on the HUD and at the other pilot's station of the mode in which the HUD is being used and of any armed modes (e.g. localizer or glide path track, flare). (…) Changes of symbology to denote the mode selected and its status are acceptable, provided they are unambiguous.

JAR-AWO H352 : Indications and Alerts

(i) An excess ILS deviation alert on the HUD and at the other pilot's station (e.g. an amber flashing light).

JAR HUDS 902 : Category 2 Operations with a Head Up Display
Issue 8, 26 avril 1995.

JAR HUDS 903 : Interim Policy – Head Up Displays.
Issue 7, 30 avril 1997.

JAR OPS 1 Sous partie E : opérations tout-temps.

JAR-OPS Section 4 / Part 3, 01 février 1999.
All Weather Operations with Head Up Display Guidance Systems (HUD).

JAA Project of interim policy
Human Factors Aspects of Flight Deck Design, Issue 2, 15-03-2001.

FAA regulation

FAR PART 25, May 27, 1998.
Airworthiness Standards: Transport Category Airplanes.

Main rules applicable to HUD :

25.773 Pilot Compartment View
25.777 Cockpit Controls
25.1303 Flight & Navigation Instruments
25.1321 Instruments: Arrangement & Visibility : the "Basic T".
25.1323 Airspeed Indicating System
25.1331 Instruments Using a Power Supply
25.1333 Instrument Systems
25.1335 Flight Director Systems
25.1381 Instrument Lights

FAA AC 120-28D et appendices, 13 juillet 1999.
Criteria for Approval of Category III Weather Minima for Takeoff, Landing and Rollout.

FAA AC 120-29A et appendices, draft 18, 1999.
Criteria for Approval of Category I and Category II Weather Minima for Approach

FAA AC 25-11, 16 juillet 1987.
Transport Category Airplane Electronic Display Systems.

FAA Dale Dunford
Head Up Display – Certification Factors for Transport Airplanes.
Los Angeles ACO, 21 septembre 1996.

Discusses several factors which are specific to HUDs and which should be addressed during the certification process :

- System Safety Assessment
- Visibility and Field-of-View
- "Basic T" Deviations (see AC 25-11)
- *Clutter* vs. Information Content ("a design challenge")
- Unusual Attitude Recovery (needs to support attitude awareness, recognition and recovery – must be usable in nominal and dynamic, unusual conditions)
- Monochrome Limitations (HUDs lack color, symbology must compensate)

FAA DOT/FAA/CT-96/1
Human Factors Design Guide

**FAA HUD Certification Criteria - Working Paper.
7 septembre 2000.**

FAA Issue Papers, for each Part 25 HUD certification…

**FAA Memorandum, 25 février 1992.
POLICY: Airspeed Displays for Electronic Flight Instrument Systems (EFIS)
Transport Airplane Directorate, Aircraft Certification Service, ANM-100**

**FAA Memorandum, 12 septembre 1996.
POLICY: Low and High Speed Awareness Cues for Linear Tape Airspeed Displays
Manager, Transport Airplane Directorate, ANM-100.**

Documentation SAE

**SAE AIR 4742, Head-Up Display Issuing Committee, mars 1998.
Display Characteristics of FDI Head-Up Guidance System as Approved for the B-727 Airplane.**

> *The scope of this document is limited to descriptions of the display characteristics of the Flight Dynamics, Inc. (FDI) Model 1000WS Head up Guidance System (HGS) as installed on the Boeing 727 airplane and certified by the Federal Aviation Administration for use in Category III landing operations. The symbology depicted in this document is referenced to the particular pilot task(s) for which it was designed. Also included are descriptions of operational features of the particular symbol along with any associated criteria regarding symbology constraints, source data, or position error.*

SAE ARP 4102/8, novembre 1998.
Flight Deck, Head-Up Displays

> *This document recommends criteria for the design and installation of Head-Up Display (HUD) systems. The recommendations are applicable to HUD systems which display flight information focused at infinity in the forward field of view. This annex does not address devices for peripheral vision or displays worn by the pilot, nor the presentation of EVS information.*

SAE ARP 4155, Aerospace Behavioral Engrg Technology, octobre 1997.
Human Interface Design Methodology for Integrated Display Symbology

> *The recommended design approach is described in Figure 1. The approach emphasizes the fundamental relationship between symbols, the information they encode, the context within which the symbols are displayed, and the tasks being supported. While this document is aimed at aircraft displays involving dynamic control or monitoring tasks, the methodology is applicable to a wide range of symbology development situations.*

**SAE ARP 5288, draft 12, 19 janvier 2000.
Transport Category Airplane Head Up Display (HUD) Systems.**

**SAE AS 8055, A-4 Aircraft Instruments Committee, mars 1999.
Minimum performance Standard for Airborne Head Up Display.**

> *This SAE Aerospace Standard (AS) specifies minimum performance standards for airborne binocular Head Up Displays (HUDs) in fixed wing aircraft. This document covers criteria for conformal and non-conformal HUD systems that are intended for use in the cockpit by the pilot or copilot. Display minimum performance characteristics are specified for standard and other environmental conditions for the purpose of product qualification. This document does not address sensor imaging systems, displays worn by the pilot (goggles, helmet mounted displays) or specific symbology to be displayed.*

Appendix 6 : Synthesis of the existing regulations

	Origin			Status				Purpose			Instrument			Operation				Concept	
Regulation	JAA	FAA	Autre	Applicable requirement	Means of compliance	Certification issue	Draft regulation	Conception	Certification	Operations	All instruments	EFIS	HUD	All operations	Category I	Category II	Category III	Manual	Monitoring & Hybrid
JAR 25	x			x				x	x		x			x					
HUDS 903	x			x				x	x				x	x				x	x
HUDS 902	x			x				x	x				x			x		x	x
HUDS 901	x			x				x	x				x				x	x	
JAR AWO	x			x				x	x				x			x	x		x
JAR OPS 1/E	x			x						x	x					x	x		x
JAR OPS 4/3	x			x						x			x			x	x	x	x
AMJ 25-11	x				x				x			x		x					
CRI	x					x			x		-	-	-	-	-	-	-	-	-
FAR 25		x		x				x			x			x					
AC 25-11		x			x			x				x		x					
AC 120-29a		x			x				x	x			x		x	x		x	x
AC 120-28d		x			x				x	x			x				x	x	x
Memorandum		x			x				x		-	-	-	-	-	-	-	-	-
IP		x				x			x		-	-	-	-	-	-	-	-	-
SAE ARP 4102/8			x	x				x					x	x				-	-
SAE ARP 5288			x				x	x					x	x				x	x

NB : a dash indicates a possibility, depending on the text considered in particular.

Appendix 7 : Explicit regulation requirements concerning HUD symbologies

	All OPS		Category II		Category III	
	SAE ARP 4102/8	JAA HUD 903	FAA AC120-29a	JAA HUD 902	FAA AC120-28d	JAA HUD 901
Airspeed	**X**	**X**	>	>	>	>
Altitude	**X**	**X**	>	>	>	>
Pitch & roll attitude	**X**	**X**	>	>	>	>
Heading	**X**	**X**	>	>	>	>
Velocity vector	x	x	>	>	>	>
Potential flight path	r	x		>		>
Wind effects	x	x	>	>	>	>
Side slip effects	x	x	>	>	>	>
Vertical speed	x	x	x	>	>	>
Radio altitude	r		x	x	x	x
Excess ILS deviation			r	x	f	x
Position on the ILS			x	x	x	x
Marker indication			x		>	
DH indication			x	x	>	x
ILS guidance	x		m	f	>	>
ILS capture				x	x	x
Navigation source			x		>	
Mode HUD					x	x
Mode AP in operation	x	x	x	x	>	x
Mode auto throttle						x
Runway symbol						f
Failure indication	x	x	x	x	x	x
ILS intercept			f		f	f
Go around			f	f	x	x
Flare guidance			f		f	f
Roll out guidance			f		f	f

Legend : **X** : requirement of the basic T
x : requirement m : requirement for manual control
> : requirement derived from a more general regulation document
f : optional functionality, subject to requirement if available
r : recommendation

Appendix 8 : Test engineer questionnaire

Name : **Organisation :**

Subject : HUD Certification : the regulation, its interpretation, your experiences and the main problems encountered...

What are your main experiences of HUD certification ?

Could you describe the usual HUD certification process ?

What is your role in this process ?

What are the regulation documents used (FAA, JAA, other) ?

Could you comment the quality / adequation of these documents with your needs ?

Do you make use of non regulatory references ? What do they add to the regulation ?

Which texts specifically deal with HUD symbology ?

Does the certification address some characteristics of the symbology in particular ? Namely :

- information to be displayed ?
- symbol shape and location ?
- analogue vs digital representation ?
- conformality ?
- other ?

What are the technical and human factors issues known with the HUD ?

What about the compatibility between the HUD and the flight deck ? between the HUD and the right seat ?

Could you describe some typical situations or scenarios known for the difficulties they raise for the use of a HUD ? What are the solutions ?

What are the human factors addressed during the certification ?

Could you describe the typical HUD user (qualification, experience, actual use of the HUD) ?

What are the methods or criteria used to address the human factors issues during the certification process ?

What is your freedom to interpretate the regulatory documents ?

Could you relate some difficulties you have met among a certification team because of a different regulation interpretation ?

Is it possible to solve these varying opinions ? How ?

Do you have an operational information feedback about the use of the HUD, once the certification is achieved ?

Historically, which changes have happened in the certification process ? What are the main benefits and/or constraints ?

Could you mention some lacks or defaults of the current regulation ? Concerning for instance :
- the design of the HUD ;
- the certification process ;
- the operational use ;
- the organisation / quality of the regulation documents ?

What would you recommend to compensate for these defaults ?

What do you think will be the next trends of the use of the HUD ?

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Appendix 9 : Test pilot questionnaire

Name : **Organisation :**

Subject : Your HUD experience : certification, use and difficulties encountererd...
Objective : Identify the possible HF weaknesses of civil transport HUD symbologies, how they're exploited during certification, in order to orient our recommendations for an evolution of the regulation concerning HUD symbologies.

<u>Concerning the HUD certification process :</u>

What are your main experiences in HUD certification and use ?

Role of the test pilot ?

Use of the regulation ?

Which methodology ?

Is there a systematic approach to evaluate a symbology ?
What are the main aspects you think have to be addressed ?
What means do you use during the certification process ?
Out the certification constraints, which methods / means do you think should be used ?

Who is the reference pilot ?

What is the typical background, experience, familiarity in the use of the HUD ?
Do you have some practical examples of difficulties in the use of the HUD ?
What is your experience in line ? Does this experience influence your practice of certification ?

<u>Concerning the symbology :</u>

Could you describe some typical HUD symbologies (paper work) ?

Are there different design conceptions ?
With which symbology are you the most familiar ?

Comments on the information to be displayed : needed or not / possible difficulties

	Flight phase (Needed ? For which ops / cat I/II/III ?)					Problems ?
	roll out	take of	cruise	approach	goaround	
attitude (pitch/roll)						
altitude baro						
airspeed / ground sp						
vertical speed						
heading						
velocity vector						
speed deviation						
potential flight path						
radio height						
side slip angle						
load factor						
ILS guidance						
navigation						
propulsion						
modes AP						
warnings						

Comments on the symbology charactericstics :

colour / shape / size / location
analogue / digital
collimation
conformity
head down compatibility
field of view / caging
clutter / declutter modes

Symbology and regulatory requirments

The following tables presents some extracts of the JAA regulation. Please fill the table with what you think is(are) the corresponding symbol(s) required, and whether it should be situation (s) or guidance (g) information.

NB : (1) = JAR HUDS 901 - (2) = JAR HUDS 902 - (3) = JAR HUDS 903

Flight phase	Requirements	Symbology		
			s	g
all	- Both digital and analogue representations of airspeed, altitude, vertical speed and heading must be provided and positioned using the basic T format (3) The minimum acceptable information ... must include : clear and unambiguous indication of pitch and roll attitude, sufficient information to permit a rapid evaluation of the aircraft's energy state and position(e.g. altitude, airspeed, vertical speed and heading) during each flight phase for which approval is sought (3) - clear and unambiguous indication of pitch and bank (1) - clear indication of non-conformal positioning of normally conformal elements (1,3) - the mode in which the autothrottle is operating (1) - a positive and continuous indication of the mode in which the HUD is being used and of any armed modes (1,2) - to monitor automatic and manual flight guidance modes and system status (2,3) - the pilot using the HUD will need to have his attention brought to any changes of mode (normal or uncommanded) (2)			
approach and landing	- to intercept the ILS app. path, to track it, to land (1) - an excess ILS deviation alert (1,2) - arrival at DH, height must be positively annunciated (1,2) - radio altitude (2) - clear visual indication on the HUD when the aeroplane reaches the preselected DH (1,2) - to monitor the HUD system operational status and approach performance continuously without referring to the head down displays (1)			

go around	- to make a go-around without reference to other cockpit display (1) - sufficient info. to initiate and stabilise a go-around at any point during the app. and flare without reverting to other displays (1,2) - an appropriate indication or warning of on-engagement of go-around mode when it is selected (2)			
roll out	- to control the aeroplane along the runway after touchdown within the prescribed limits (if ground control guidance is provided on the HUD) (1)			
take off				
failures	- in the event of an engine failure HUDs must permit to control the aeroplane without reverting to others displays (1) - if radio alt failure, the warning must be given by removal or obscuration of displayed information at least in the height band from 30m downwards (1)			
unusual situations				

Human factors :

What are the main difficulties for training ?
What about the following issues :

- workload,
- attention effects,
- information confusion or ambiguity,
- masking of the external situation,
- spatial disorientation,
- unusual situations,
- effect of the use of the HUD on crew team management ?

Operational use of the HUD once certified

Do you have an operational information feedback ?
Could you relate some example cases of safety events that have occurred with a HUD ?
What do you hear is the opinion of the airline pilots about the use of the HUD ?
Do you know the reasons why the HUD is not used on some equipped aircraft ?

Next changes in the HUD symbology and regulation

Is there a need for research study on one particular HUD issue ?
What will be the next HUD concepts to be certified ?
What do you think will be the effects of the coming changes in the aeronautical system (for the use of a HUD) ?
Which improvements would you recommends in the current regulation ? in the usual certification process ?
What about the JAA / FAA regulation harmonisation ?

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Appendix 10 : Comparison of the opinion of two test pilots concerning the relevance of some symbols, depending on the flight phase.

	Taxi	T/O	Cruise	Appr. VMC	Appr. cat. I	Appr. cat. II	Appr. cat. III	GoA	Engin e fail.	Unus sit
Airspeed	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Altitude	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Attitude	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Heading	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	
Velocity vector	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Potential flight path	+	**+**		**+**	**+**	**+**	**+**	**+**	**+**	
Wind (dir. and force)				**+** +	**+** +	**+** +	**+** +			
Sideslip				+	+	+	+			
Vertical speed	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
Radio altitude					+	**+**	**+**			
Excess ILS deviation					+	+	+			
ILS raw data					+ **-**	+ **-**	+			
Marker indication					**+**	**+**	**+**			
DH indication					**+**	**+**	**+**			
ILS guidance					+	+	+			
ILS capture										
Navigation sources										
Mode HUD										
Modes AP in ops	+ **-**	+ **-**	+ **-**	+ **-**	+ **-**	+ **-**	+ **-**	+ **-**	+ **-**	
Mode auto throttle										
Runway symbol					+	+	**+**			
Alarme	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	
ILS intercept										
Go around										
Flare guidance										
Roll out guidance										
Roll indicator								+	+	
DME range					+ **-**	**+ -**	**+ -**			
Ground speed	+ **-**	+ **-**	+ **-**	+ **-**	+ **-**	+ **-**	+ **-**	+ **-**	+ **-**	**-**
Speed deviation	**-**	+		+	+	+	+			
Selected speed		**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
Speed scale & limits		+								

Legend :
- **bold** symbol subject to a regulatory requirement (see Appendix 7)
- *italics* divergent opinions
- ▢ (grey) non discussed during the interviews
- **+** necessary symbol
- + useful symbol
- **-** useless symbol

Appendix 11 : Synthesis of 16 HUD related ASRS reports

Source : ASRS search request n°6169, June 15, 2001

Report number	Date Place	Aircraft type	HUD implication	Circumstances	Other facts
1/133705	1990 CA	Fighter	HUD used as a PFD ; freeze symbology	Loss of control (0 kts) recovery on backup instruments	Crew did not eject due to proximity of built up area.
2/138647	1990 US	3 turbojet engines	Align HUD annunciator clear for several minuts	Crew distracted by the HUD. Non adherence to alt restrictions.	Argument with the airline dispatch.
2/168235	1991 AK	3 turbojet engines	Used for approach with snow obscuration	Runway incursion of another a/c. Communication defaults with ATC.	
4/197645	1991 AK	3 turbojet engines	Wind data displayed on the HUD enhanced the decision process to abort 2 landings.	High winds and wind shear approach. The HUD was very valuable in making the decision to go around.	
5/223355	1992 AK	3 turbojet engines	HUD used in cat III approach, still in auto test at 1000 ft AGL.	During practice cat. III approach, speedbrake default resulting in crew distraction and alt and speed deviation.	FAA in the jumpseat
6/299958	1995 CA	B 737-300	A manual approach with a HUD would be a better approach.	Encountered wake turbulence behind a B-737 4 nm ahead. AP has to be disconnected.	
7/314184	1995 MI	Dornier 328	None	Electrical failure causing non relevant messages, one concerning the HUD.	
8/371632	1997 AK	Commuter Fixed wing	None	False warning displayed on PFD and HUD plus stick shaker activation, due to AOA sensor damaged.	
9/391408	1998 AK	B 737-400	HUD used as backup by the PNF without no cross checks with the HDD.	PF fly a manual approach but inadvertent selection of wrong mode. Recovery by EGPWS signal.	
10/423675	1998 NY	B 727-100	None. HUD used for ILS guidance during the approach.	Long landing and reported poor braking conditions resulted in runway departure.	
11/452301	1999 GA	B 737-800	The copilot believes the CPT was too much focused on the HUD that a lost SA for a moment.	Aircraft directed to go around by tower. Poor ATC communication resulted in a TCAS resolution advisory.	

12/453091	1999 US	B 737-700	None	During a test flight with CPT monitoring with the HUD, the a/c made a touch and go without having clearance.	
13/456663	1999 US	B 737-300	The HUD is credited for being able to fly a precise maximum climb.	The CPT has to avoid an intruding a/c at take-off, performing a max climb with the help of the HUD.	The CPT had previous military experience with the HUD so find it natural to use in the avoidance maneuver. He thinks the FAA should require all a/c to be equipped with HUDs.
14/462540	2000 PA	B 727-200	None. HUD used for localizer monitoring.	Flight instruments give false contradicting indications. Approach completed in VFR conditions.	Water was found in the electronic bay…
15/487446	2000 IL	B 737-300	HUD provided some flight information during a multiple display failure.	Loss of EFIS displays due to a connection default in cruise. The a/c declared an emergency and diverted.	No check list is provided in case of a multiple display failure.
16/502070	1999 AZ	PA 28 Cherokee F 16	None. The F 16 HUD video tape is used to review the event.	A patrol of F16 practised visual ident of the PA 28, and caused him to perform an evasive action as they went too close.	

Appendix 12 : Technical documentation on existing HUDs

Flight Dynamics (1996, avril).
Head-Up Guidance System – HGS Model 2100 – Canadair Regional Jet

Bombardier (1997, juin & 1996, janvier).
HGS Canadair Regional Jet Flight Crew Operating Manual : Description & Limitations

Bombardier (2001, juin).
HGS Canadair Regional Jet Flight Crew Operating Manual : Temporary revision RJ/92.

Rockwell Collins Flight Dynamics (2000, mai).
Head-Up Guidance System Model 4000 – HGS Pilot Guide – Boeing 737 NG

BAE Systems (2000, janvier).
Pilot’s Guide for the Visual Guidance System for Boeing 737 NG Aircraft, issue 3.

AIR France DT-NT (1999).
Navigation HUD – A319/20/21*, 25 février 1999*.

Sextant Avionique (1997)
HFDS – MD82 Training Syllabus rev. B – Alitalia, 21 mai 1997

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Appendix 13 : Airline user questionnaire

Airline : **Date of the interview :**
Name of the user : **Experience of the user :**

1 History of the use of HUD in the airline

2 Current use of the HUD in the airline

Information on the HUD equipment

Description of the HUD ? Main characteristics of the symbology ?
Was the airline involved in its design ? in its certification ?
On which aircarft type is it installed ? On every aircarft of the fleet ? On all the lines ?
Could you provide a documentation describing the HUD ?

What are the procedures currently in use ?

Please fill up the table below (using M for manual use, A for monitoring of the automatic mode)

The use of the HUD is :	Operation									
	taxi	take-off	cruise	appr. VMC	appr. cat. I	appr. cat. II	appr. cat. III	go-around	engine failure	unusual sit.
Mandatory										
Recommended										
Possible										
Forbidden										

What do you think are the reasons for the choice of this HUD equipment ?
Could you describe the current procedures for the most frequent use ?
Have they been modified following difficulties encountered in flight ? Which ones ?
Could you provide a documentation describing the current procedures ?

3 Advantages and disadvantages of this HUD ?

Sociological aspects

Are the users happy with this HUD ? How much is it used ?
Does the HUD help the conversion from one aircraft type to another ?
Are there any difficulties sometimes encountered in the use of the HUD during these conversion ?
What are the main factors affecting the use of the HUD : the user's experience ? age ? airline ? other ?

Economical and operational aspects

What is the main benefit for the use of the HUD ?
Is there a means to exactly measure the impact of the HUD on the operations ?
Could you provide some evaluation data (e.g., the number of take-off / landings which wouldn't have been possible without the HUD) ?

Safety aspects ?

Could you describe some exmple of difficulties or incidents linked to the use of the HUD ?
On the opposite, could you provide some example situations in which the HUD contributed to safety ?

To improve this HUD…

Which modification would you suggest ?

4 The official policy of the airline concerning the use of HUD ?

In general ?

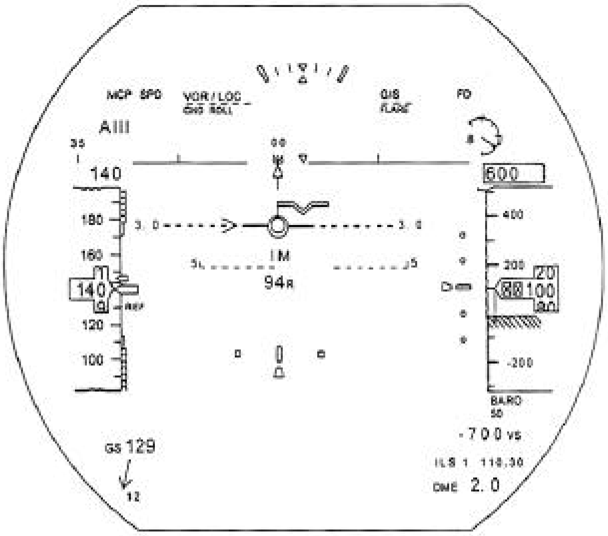
For the future of the airline ?

Will the airline buy some HUD for its existing aircraft ? For its future aircraft ?

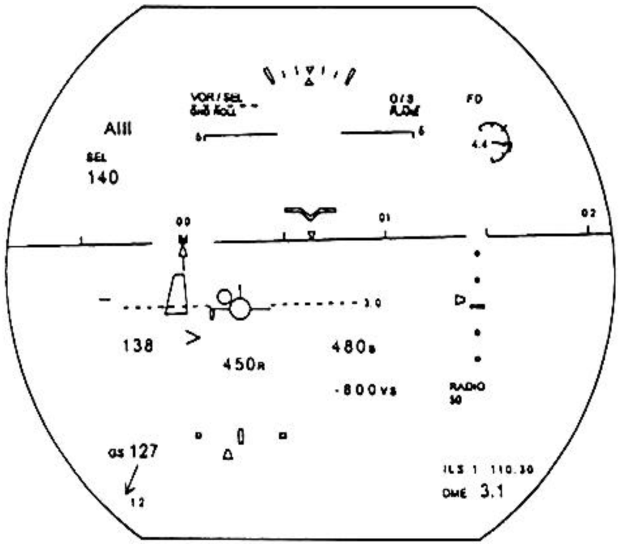
5 Other comments, next contacts, suggestions for the study ?

Appendix 14 : Comparison of symbologies for cat. III approach

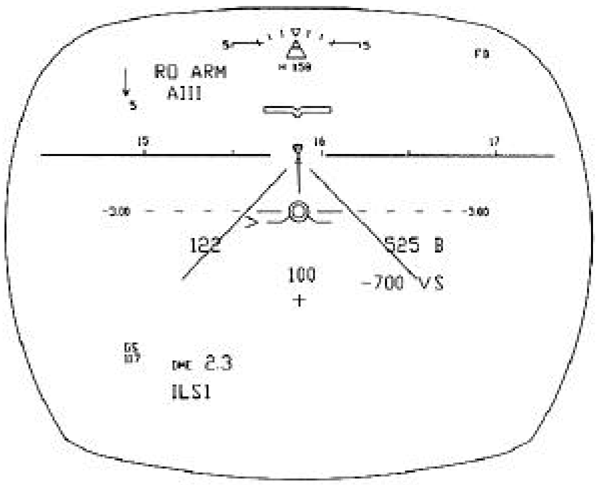
a) Symbologies HUD ayant permis d'établir les tableaux comparatifs "approche cat. III" (cf. pages suivantes)



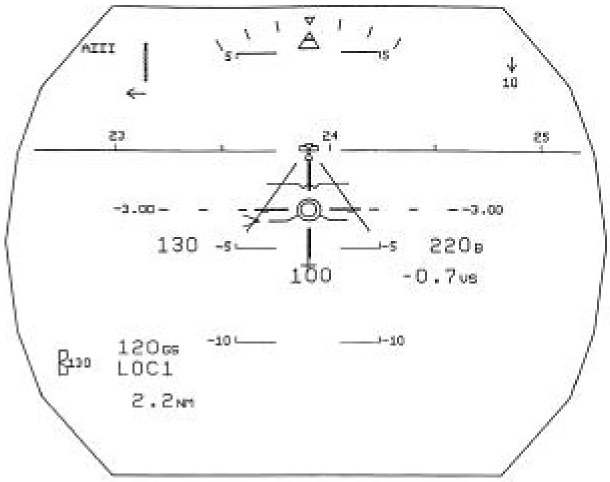
VGS Baé B737 NG - Mode AIII Normal



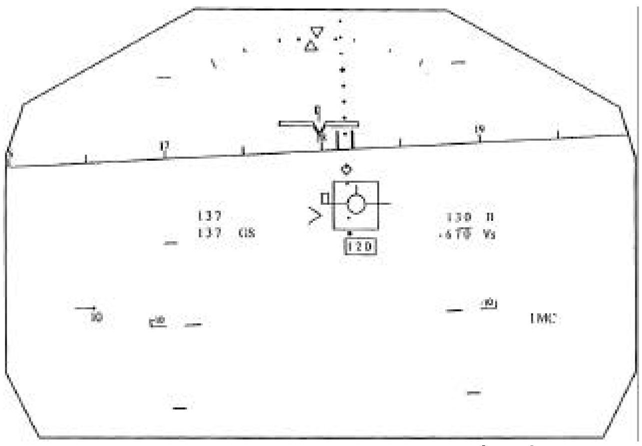
VGS Baé B737 NG – Mode AIII Declutter



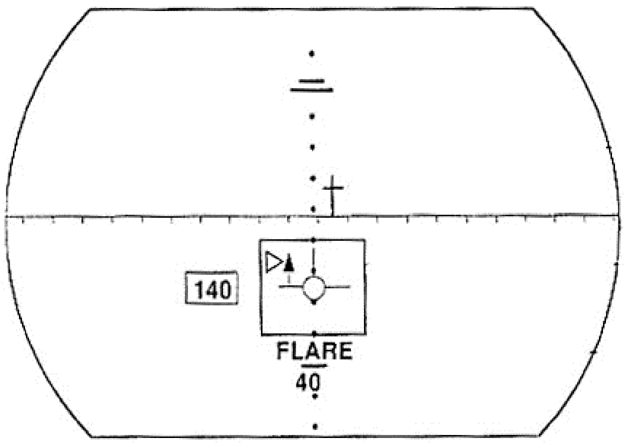
HGS Flight Dyn. B737 NG - Mode AIII



HGS Flight Dyn. CRJ 100 - Mode AIII



HFDS Sextant MD 82 - Cat IIIB autoland



HUD Sextant A320 - Approche ILS

b) Comparison of the symbologies for the cat. III approach mode.

	Manual			**AP monitoring**	
	B737 NG BAé systems	**B737 NG Flight Dyn.**	**CRJ Flight Dyn.**	**MD 82 Sextant**	**A 320 Sextant**
Airspeed	num	num	num	num	num + box flashing at VLS-5
Altitude	num B	num B	num B	num B	∅
Attitude pitch and roll	pitch scale + horizon	pitch scale + horizon	pitch scale + horizon	pitch scale + horizon	pitch scale + horizon
Heading	scale + ind	scale + ind + H num	scale + ind	scale	bare scale
Velocity vector	analogue	analogue	analogue	analogue	analogue
Potential flight path	chevron	chevron	chevron	chevron	analogue
Wind (dir. & speed)	arrow + num	arrow + num	arrow + num	arrow + num	∅
Side slip angle	flag analo	forme analo	forme analo	flag analo	∅
Vertical speed	num VS	num VS	num VS	num VS	∅
Radio height	num R	num	num	num (box at DH+100)	num
ILS position	glide&loc scale	ILS bars	ILS bars	raw deviation	raw deviation
Excess ILS deviation	EXCESS DEV	flashing bars	flashing bars	box	box
Marker indication	abbreviations	abbreviations	abbreviations	abbreviations	∅
DH indication	MINIMUMS	DH	DH	DH	DH
ILS guidance	FD circle	FD circle	FD circle	∅	∅
ILS capture	glide&loc scales	ILS bars	ILS bars	box closed	box closed
Navigation source	ILS num+ freq	ILS num	LOC num	∅	∅
Mode HUD	abbreviations	abbreviations	abbreviations	abbreviations	∅
Mode PA in ops	abbreviations	abbreviations	abbreviations	∅	∅
Mode auto throttle	abbreviations	abbreviations	∅	∅	∅
Runway symbol	rwy outline	rwy edlgelines	rwy edlgelines	rwy centerline	∅
Approach warning	NO AIII	APCH WARN	APCH WARN	∅	∅
Roll indicator	scale + index	scale + index	scale + index	scale + index	∅
Distance DME	DME num	DME num	DME num	∅	∅
Ground speed	GS num	GS num	GS num	GS num	∅
Selected speed	Sel num	AS num	shape num	∅	∅
Speed deviation	analogue	analogue	analogue	analogue	chevron
Speed scale & limits	∅ if declutter	∅	∅	∅	∅
Altitude scale & limits	∅ if declutter	∅	∅	∅	∅
Course	VV / scale cap	VV / scale cap	VV / scale cap	VV / scale cap	∅
Selected course	index / hdg scale	index / hdg scale + CRS num *temp*	index / hdg scale + CRS num *temp*	∅	∅
Selected heading	index / hdg scale	index / hdg scale + HDG num *temp*	index / hdg scale + HDG num *temp*	index / hdg scale	∅
DH value	RADIO num	∅	DH num *temp*	∅	∅
Reference ILS slope	line x° glide	line x° glide	line x° glide	∅	∅
AoA indicator	scale + num	∅	∅	∅	∅
Flare guidance	cue / FD	cue / FD	cue / FD	fixed diamond	FLARE
Message idle	RETARD	IDLE	IDLE	∅	∅
Excessive pitch	TAILSTRIKE	∅	∅	∅	∅

Legend : ∅ : not displayed num : digital value analo : analogue presentation
temp : symbol only temporary displayed, usually after a selection.
XXX : alphanumeric indication as displayed on the HUD.

c) Classification of the symbols according to their commonality between the existing HUD products

	Manual		AP monitoring	
	Common basis	**Particular**	**Common basis**	**Particular**
Airspeed	●		●	
Altitude	●			●
Pitch and roll attitude	●		●	
Heading	●		●	
Velocity vector	●		●	
Potential flight path	●		●	
Wind (dir. and speed)	●			●
Side slip angle	●			●
Vertical speed	●			●
Radio height	●		●	
Excess ILS deviation	●		●	
ILS position	●		●	
Marker indication	●			●
DH indication	●		●	
ILS guidance	●			
ILS capture	●			
Navigation source	●			
Mode HUD	●			●
Modes AP in ops	●			
Mode auto throttle		● (*)		
Runway symbol	●			●
Approach warning	●			
Roll indicator	●			●
Distance DME	●			
Ground speed	●			●
Selected speed	●			
Speed deviation	●		●	
Speed scale & limits		● (declutter)		
Altitude scale & limits		● (declutter)		
Course	●			●
Selected course	●			
Selected heading	●			●
DH value		●		
ILS reference slope	●			
AoA indicator		●		
Flare guidance	●		●	
Message idle	●			
Excessive pitch		●		

(*) : except the CRJ 100 which has no auto throttle.

Appendix 15 : Comparison of the symbologies for take-off roll and roll-out

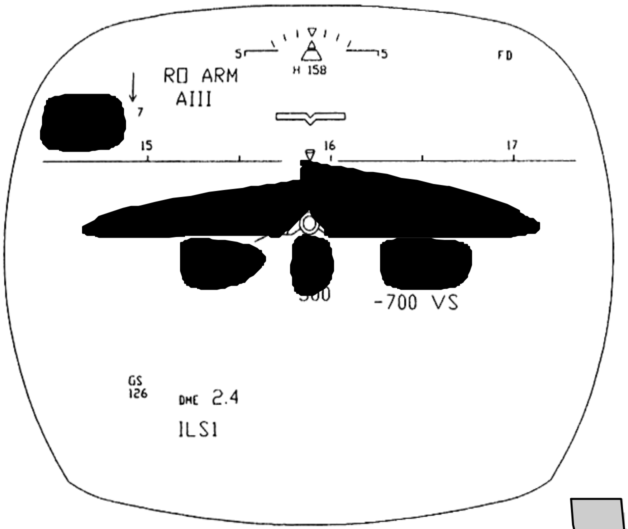
	Manual			Hybrid	
	B737 NG BAé systems	**B737 NG Flight Dyn.**	**CRJ Flight Dyn.**	**MD 82 Sextant**	**A 320 Sextant**
Airspeed	num + scale	num (+ scale if not *AIII*)	num (+ scale if not *AIII*)	num (> 30 kts)	num + box
Altitude	num + scale	num + scale (∅ if *AIII*)	num + scale (∅ if *AIII*)	∅	∅
Pitch and roll attitude	a/c symbol + horizon	a/c symbol + horizon	a/c symbol + horizon (+ pitch scale if not *AIII*)	a/c symbol + horizon + pitch scale at sel. hdg	a/c symbol (+ horizon if *TO*)
Heading	scale / horizon	scale / horizon	scale / horizon	scale / horizon	scale (no labels) / horizon if *TO*
Ground velocity vector	analogue + legs	analogue (if guidance)	∅	∅	∅
Acceleration	chevron	chevron	chevron	∅	∅
Side slip angle	∅	analogue	analogue	∅	∅
Vertical speed	num VS	∅	∅	∅	∅
Position on the ILS	raw loc. line	raw loc. line	raw loc. line	∅	∅
Info. nav. source	ILS num+ freq	ILS num	LOC num	∅	∅
Mode HUD	abbreviations	abbreviations	abbreviations	∅	∅
Mode AP in ops	abbreviations	abbreviations	abbreviations	TOGA/IMC	∅
Mode autothrottle	abbreviations	abbreviations	∅	∅	∅
Runway symbol	∅	∅	∅	rwy centreline	∅
Warning	∅	LOC CMP	flags	rwy centreline disappear	∅
Roll out guidance	∅	FD circle	∅	∅	FD yaw bar
Roll scale	scale + index	scale + index	scale + index	∅	∅
Distance DME	DME num	∅	num NM	∅	∅
Ground speed	GS num	GS num	∅	num GS	∅
Speed deviation	∅	∅	∅	∅	∅
Selected speed	num	num	forme num trans	∅	∅
Selected route	index / horizon	index / horizon + CRS num	index / horizon + CRS num trans	∅	∅
Selected heading	∅	index / horizon + HDG num	index / horizon + HDG num trans	index / horizon	∅
Selected altitude	num	num (if not AIII)	num (if not AIII)	∅	∅
Rotation guidance *(TO)*	pitch line 10°	pitch line FD	pitch line 10 or 15° then FD	∅	∅
Angle of attack	scale + num	∅	∅	∅	∅
Runway remaining	RWY REM num	RWY num	∅	∅	∅
Reference speed *(LDG)*	∅	∅	V1, V2, VR, VT	∅	∅
Deceleration *(TO)*	∅	scale	∅	∅	scale

∅ : no symbol *AIII* : AIII mode
TO : take-off roll *LDG* : landing roll out

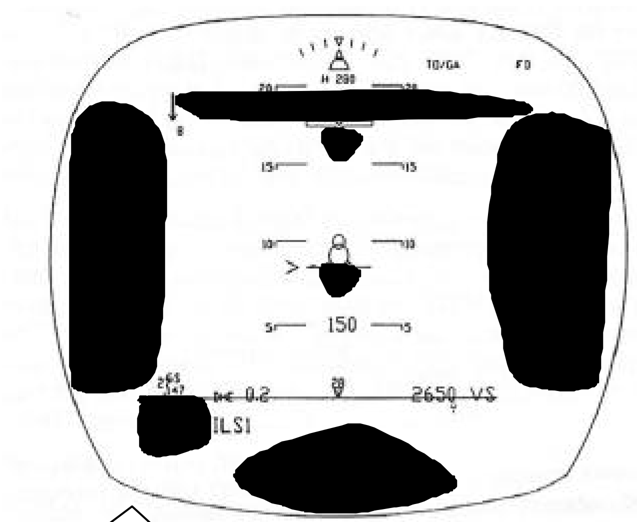
Appendix 16 : Comparison of the symbologies for transitions (go-around and rotation)

a) Some examples of symbology changes during an aborted cat. III approach

HGS Flight Dynamics B737 NG

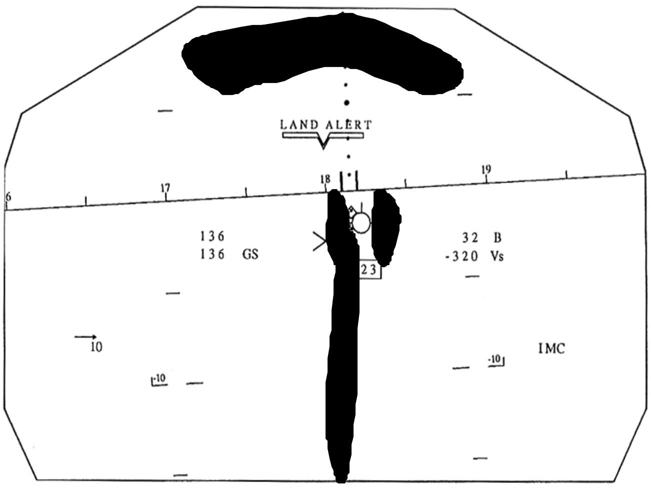


AIII mode

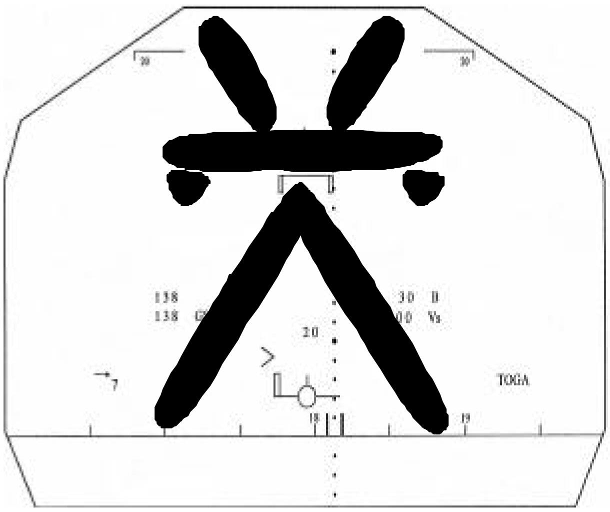


TO/GA mode

HFDS Sextant MD 82



Cat IIIB autoland



Go around

Note :
On the left figures, the underlined symbols are those which disappear during the go-around.
On the right figures, the underlined symbols are those which appear during the go-around.

b) Comparison of symbology changes occuring at go-around (cat. III approach)

	Manual			Monitoring
	B737 NG BAé systems	B737 NG Flight Dyn.	CRJ Flight Dyn.	MD 82 Sextant
Loc. deviation	Disappear			Disappear
Glide deviation	Disappear			Disappear
Glide ref. line	Disappear			∅
Runway symbol	Disappear			Disappear
Roll scale + index	Maintained			Disappear
Wind (dir. & speed)	Maintained			Maintained
Altitude	num → scale + num			num maintenu
Airspeed	num → scale + num			num maintenu
FD cue	Maintained			∅
HSI nav indications	APPEARING			∅
Side slip angle	Maintained + (1)	Maintained + (2)	Maintained + (3)	Maintained
Vertical deviation	∅	APPEARING		∅
TO/GA pitch line	APPEARING		∅	APPEARING
TO/GA pitch scale	∅			APPEARING
One engine pitch reference	∅			APPEARING

c) Comparison of symbology changes occuring at take-off rotation

	Manual			Monitoring
	B737 NG BAé systems	B737 NG Flight Dyn.	CRJ Flight Dyn.	MD 82 Sextant
Ground loc. line	Disappearing			Disappearing
Rwy remaining	Disappearing		∅	∅
Pitch scale	APPEARING		Maintained	APPEARING
FPV	Shape is modified		APPEARING	APPEARING
FD cue	APPEARING	Maintained	APPEARING	∅
Altitude	Maintained			APPEARING
Radio altitude	APPEARING			APPEARING
Vertical speed	Maintained	APPEARING		APPEARING
HSI nav indications	∅	APPEARING		∅
Side slip angle	APPEARING	Maintained + (2)	Maintained + (3)	APPEARING
Wind (dir. & speed)	∅	APPEARING		APPEARING
Distance DME	Maintained	APPEARING	Maintained	∅
Vertical deviation	∅	APPEARING		∅
TO/GA pitch line	Maintained	APPEARING	∅	APPEARING
TO/GA pitch scale	∅			APPEARING
One engine pitch reference	∅			APPEARING

Legend of these two tables :
TO/GA : Take-Off/Go-Around FPV : Flight Path Vector FD : Flight Director ∅ : not displayed
(1) = additional symbol above the a/c reference symbol in case of engine failure
(2) = 2 additional symbols (below the FPV and below the a/c reference symbol)
(3) = additional symbol below the FPV in case of engine failure.

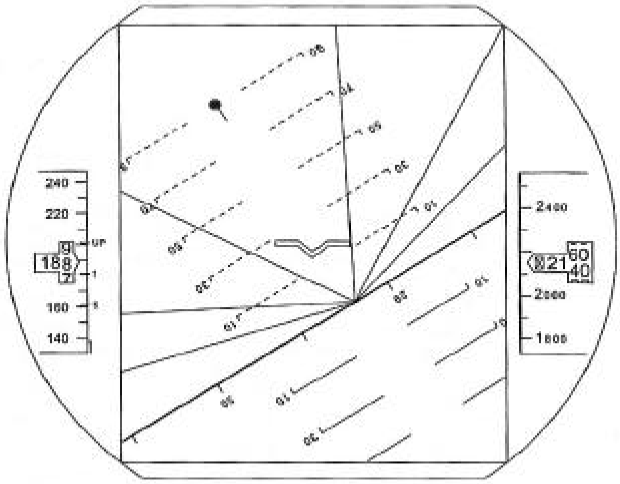
Appendix 17 : Comparison of the symbologies related to special functions

a) Comparison table

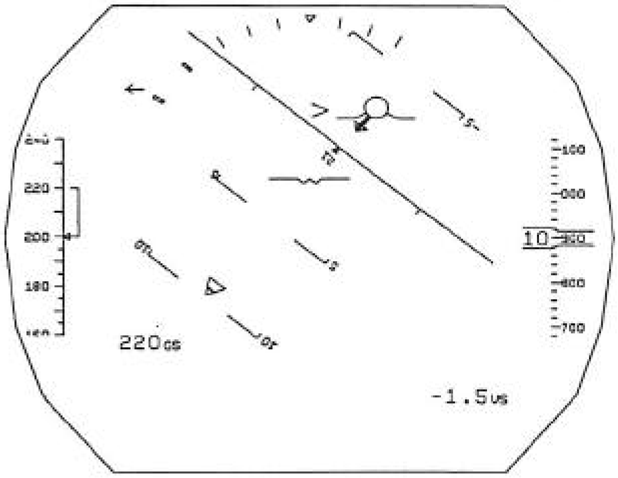
	Manual concept			**Monitoring / Hybrid**	
	B737 NG BAé systems	**B737 NG Flight Dyn.**	**CRJ Flight Dyn.**	**MD 82 Sextant**	**A 320 Sextant**
Unusual situation	Unusual attitude mode automatically selected if Pitch>35° or <-20° or Roll>55° (cf b)	Unusual attitude symbology automatically selected if Pitch>35° or <-20° or Roll>55° (cf b)	Unusual attitude up arrow + decluttered mode automatically selected if Pitch>30° or <-20° or Roll>65° (cf b)	∅	∅
Out-of-field symbologies	FPV ghosted	Pitch scale compressed + downward or upward pointing chevron + FPV ghosted	Pitch scale compressed + downward or upward pointing chevron + FPV ghosted	Dotted symbol.	FPV blinking
Windshear	Message « WINDSHEAR » below a/c ref. + Windshear guidance cue (if TO/GA mode)	Message « WINDSHEAR » below a/c ref. + Windshear guidance cue (if TO/GA mode)	Message « WINDSHEAR » below a/c ref. + Windshear guidance cue (if TO/GA mode)	∅	∅
TCAS	Preventive and corrective advisories (cf c)	Preventive and corrective advisories (cf c)	∅	∅	∅
GPWS	Message « TERRAIN » below a/c ref.	Message « PULL UP » below a/c ref.	∅	∅	∅

∅ : non available
TO/GA : Take-Off/Go-Around FPV : Flight Path Vector

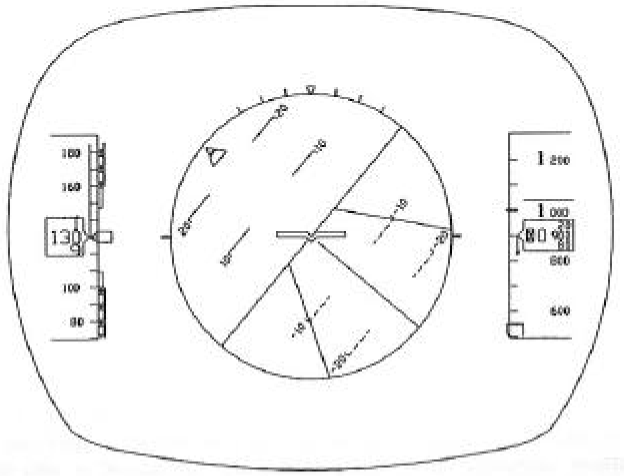
b) Unusual situation symbologies



VGS Baé B737 NG

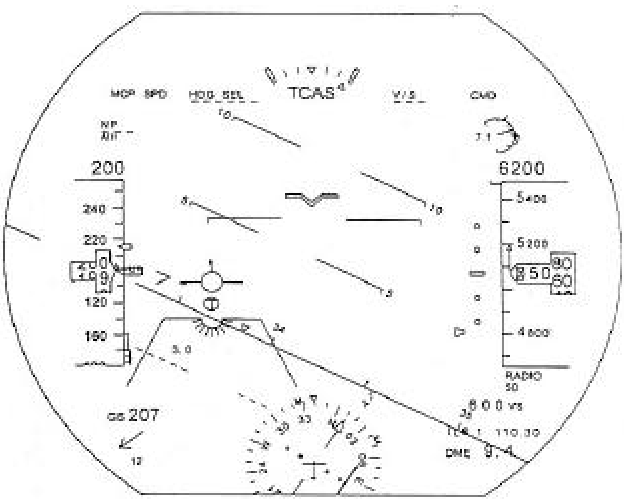


HGS Flight Dyn. CRJ 100

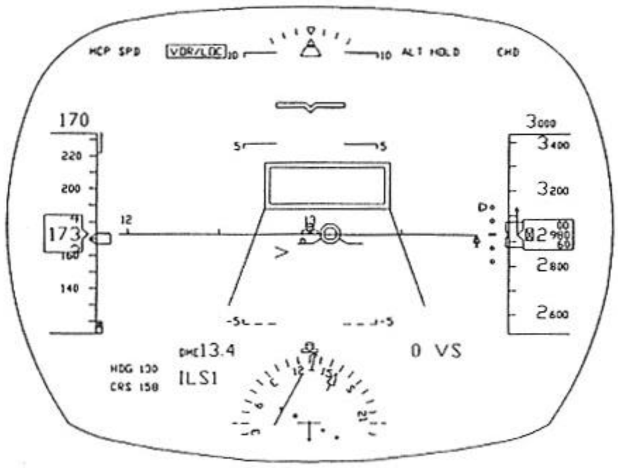


HGS Flight Dyn. B737 NG

c) TCAS symbologies



VGS Baé B737 NG



HGS Flight Dyn. B737 NG

Appendix 18 : Synthesis of the comparison of the existing HUD symbologies with the regulation (for cat. III operations)

	Manual				Monitoring or hybrid			
	Regulation		Symbology		Regulation		Symbology	
	FAA	JAA	Common	Particular	FAA	JAA	Common	Particular
Airspeed	X	X	●		X	X	●	
Altitude	X	X	●		X	X		●
Pitch & roll attitude	X	X	●		X	X	●	
Heading	X	X	●		X	X	●	
Velocity vector	X	X	●		X	X	●	
Potential flight path	r	X	●		r	X	●	
Wind (dir. and speed)	X	X	●		X	X		●
Side slip angle	X	X	●		X	X		●
Vertical speed	X	X	●		X	X		●
Radio height	X	X	●		X	X	●	
Excess ILS deviation	f	X	●		r	X	●	
Position on the ILS	X		●		X	X	●	
Marker indication	X		●		X			●
DH indication	X	X	●		X	X	●	
ILS guidance	X	X	●					
ILS captured	X	X	●					
Navigation source	X		●					
Mode HUD	X	X	●					●
Modes AP in ops.	X	X	●					
Mode auto throttle		X		●				
Symbol runway		f	●					●
Failure detection	X	X	●		X	X		
Roll scale			●					●
DME range			●					
Ground speed			●					●
Speed deviation			●				●	
Selected speed			●					
Speed scale & limits				● (all.)				
Altitude scale & limits				● (all.)				
Course			●					●
Selected course			●					
Selected heading			●					●
DH indicaton				●				
Reference ILS slope			●					
Angle of attack indication				●				
Flare guidance			●				●	
Message idle			●					
Excess pitch warning				●				

Legend : **X** : required information
f : optional function
r : recommendation

Appendix 19 : HUD bibliography

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