SAE International

SURFACE VEHICLE INFORMATION REPORT

J2716 JAN2010

Issued 2007-04
Revised 2010-01

Superseding J2716 FEB2008

(R) SENT—Single Edge Nibble Transmission for Automotive Applications

RATIONALE

Revised based on feedback from suppliers making production versions.

1. Changes meet the new EMC standard IEC 62132-4.
2. Addition of an optional pause pulse
3. Defining a new enhanced serial message as an optional replacement for the original short serial data message
4. Clarifying the diagnostics and remedial actions for successive calibration pulses comparisons
5. Added recommended modification to 4-bit checksum calculation. Recommended checksum calculation includes processing a zero nibble in addition to the data nibbles to protect for common error in last data nibble and checksum. The original CRC method is retained as an option for designs already in process or production that were developed according to previous SENT norms.
6. Added new recommended circuit topology to better handle 3.3V systems. All new sensors should use the recommended topology. The original topology is retained as an option for designs already in process or production that were developed according to previous SENT norms.
7. Added configuration shorthand notation
8. Updated MAF, Temperature and Pressure applications to take advantage of the new Enhanced Serial Message
9. Added EMC Susceptibility testing guidelines
10. Added reset action by transmitter
11. Changes for clarifications or to address typos.

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1. SCOPE

This document defines a level of standardization in the implementation of the digital pulse scheme for reporting sensor information via Single Edge Nibble Transmission (SENT) encoding. This standard will allow ECU and tool manufacturers to satisfy the needs of multiple end users with minimum modifications to the basic design. This standard will benefit vehicle Original Equipment Manufacturers (OEMs) by achieving lower ECU costs due to higher industry volumes of the basic design.

Requirements stated in this document provide a minimum standard level of performance to which all compatible ECUs and media shall be designed. This assures data communication among all connected devices regardless of supplier.

The intended audience includes, but is not limited to, ECU suppliers, sensor suppliers, component release engineers and vehicle system engineers.

1.1 Overview

The Single Edge Nibble Transmission encoding scheme (SENT) is intended for use in applications where high resolution sensor data needs to be communicated from a sensor to an Engine Control Unit (ECU). It is intended as a replacement for the lower resolution methods of 10 bit A/D's and PWM and as a simpler low cost alternative to CAN or LIN. The implementation assumes that the sensor is a smart sensor containing a microprocessor or dedicated logic device (ASIC) to create the signal.

SENT is a unidirectional communications scheme from sensor / transmitting device to controller /receiving device which does not include a coordination signal from the controller/receiving device. The sensor signal is transmitted as a series of pulses with data encoded as falling to falling edge periods. Details of the signal encoding may vary for specific sensor applications described in various appendices of this specification.

2. REFERENCES

2.1 Applicable Publications

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest version of SAE publications shall apply.

2.1.1 SAE Publications

Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

SAE J551 (All parts) Performance Levels and Methods of Measurement of Electromagnetic Compatibility for Vehicles and Devices

SAE J1113 (All parts) Electromagnetic Compatibility Measurement Procedures for Vehicle Components

SAE J1930 Electrical/Electronic Systems Diagnostic Terms, Definitions, Abbreviation and Acronyms

2.1.2 ISO Publications

Available from ANSI, 25 West 43rd Street, New York, NY 10036-8002, Tel: 212-642-4900, www.ansi.org.

None.

2.1.3 Supplier Publications

None.

2.1.4 Other Publications

CISPR 25 Limits and Methods of Measurement of Radio Disturbance Characteristics for the Protection of Receivers Used On Board Vehicles (available at webstore.iec.ch).

ES-XW7T-1A278-AC Ford Component and Subsystem Electromagnetic Compatibility Worldwide Requirements and Test Procedures (available at www.fordemc.com. This document shall be referred to as the Ford EMC Spec.)

GMW3097 General Specification for Electrical / Electronic Components and Subsystems, Electromagnetic Compatibility (this document will be referred to as the GM EMC Spec.)

3. DEFINITION OF TERMS

3.1 Glossary

3.1.1 Media

The physical entity that conveys the electrical (or equivalent means of communication) signal transmission between electronic devices.

3.1.2 Protocol

The formal set of conventions or rules for the exchange of information between electronic devices. This includes the specification of the signal frame administration, frame transfer and physical layer.

3.1.3 Message

One sequence of calibration pulse and specified number of nibble pulses for that implementation. The number of nibbles is constant for each implementation but the individual message times can vary depending on the specific values of the nibbles.

3.1.4 Radiated Emissions

The energy that radiates from the physical layer.

3.1.5 Radiated Immunity

The level of susceptibility of physical layer components to communication errors in the presence of high energy electromagnetic fields.

3.1.6 Receiver Module

The processor that receives the encoded signal. Generally an ECU with falling-edge detection and timing measurement capabilities.

3.1.7 Transmitter Module

The device that generates the message to the receiver module. Generally a smart sensor.

3.1.8 Nominal

Time period assuming no transmitter clock error.

3.1.9 Pulse Period

Time between consecutive falling edges of the transmitting signal.

3.1.10 Error

Indicates that a problem exists with current sample, data or message.

3.1.11 Fault

Indicates that enough errors have been detected (usually matured by counting X errors in-a-row or via up-down or X-out-of-Y counters or other filtering means) to develop into a fault which is latched until cleared.

4. ACRONYMS, ABBREVIATIONS, AND SYMBOLS

ASIC – Application Specific Integrated Circuit
CAN – Controller Area Network
ECU – Electronic Control Unit
EMC – Electromagnetic Compatibility
ESD – Electrostatic Discharge
ISO – International Organization for Standardization
kbits/sec – Thousands of data bits per second
LIN – Local Interconnect Network
LSN – least significant nibble
MAF – Mass Air Flow
MidLSN – middle least significant nibble
MidMSN – middle most significant nibble
MidN – middle nibble
MSN – most significant nibble
OEM – Original Equipment Manufacturer
RE – Radiated Emissions
RI – Radiated Immunity
SAE – Society of Automotive Engineers
SENT – Single Edge Nibble Transmission
TPS – Throttle Position Sensor

5. SENT SYSTEM REQUIREMENTS

5.1 General Requirements

Transmission occurs independently of any action of the receiver module, i.e. the transmission shall not require a synchronization signal from the receiver module.

Assumptions used to design the encoding scheme:

- Actual Transmission time may be dependent on the data values being sent and the transmitter clock variation.
- Message pulse order (i.e., message frame) is fixed for all transmitters.
- Transmitter is allowed a maximum clock variation of ±20%.
- Transmission time for the longest data message and max transmitter clock variation is less than 1.0 millisecond at 3 microsecond bit time and 6 data nibbles.
- A transmitter specific nominal clock period (tick) between 3 microseconds and 90 microseconds.
- The encoding scheme defines a number of diagnostic tests to be implemented in the receiving module. However, for example, the CRC checksum is 4 bit and not as robust as other checking schemes (see section 5.4.1). Therefore, the encoding scheme is targeted at systems that can tolerate a low probability of intermittent faulted messages not being detected via the scheme's diagnostic suite. In case additional robustness is needed, application level diagnostics should be used.

5.2 Message Definitions

5.2.1 Transmission Sequence

The encoding scheme consists of a sequence of pulses which is repeatedly sent by the transmitting module. The transmission consists of the following sequence (all times nominal):

- Calibration/Synchronization pulse period 56 clock ticks.
- One 4 bit Status and Serial Communication nibble pulse (defined in 5.2.2) of 12 to 27 clock ticks.
- A sequence of one up to six 4 bit Data nibble pulses (12 to 27 clock ticks each) representing the values of the signal(s) to be communicated. The number of nibbles will be fixed for each application of the encoding scheme (i.e. throttle position sensors, mass air flow, etc.) but can vary between applications. For example, if two 12 bit values are transmitted, 6 nibbles will be communicated.
- One 4 bit Checksum nibble pulse (defined in 5.2.5) of 12 to 27 clock ticks.
- One optional pause pulse (defined in 5.2.6)

Figure 5.2.1-1 shows an example single message transmission for two 12 bit sensor values assuming a 3 microsecond clock tick. Note that the shortest length message, based on a valid checksum (determined using approach documented in section 5.4.2.2) consists of 154 clock ticks (Data nibbles [0 0 0 1 1 0] and Checksum 0, Data nibbles [0 0 1 0 0 0] and Checksum 1, and Data nibbles [1 0 0 0 0 1] and Checksum 0). Similarly, the longest message is 270 clock ticks (Data nibbles [$E $F $F $F $F $E] and Checksum $F, Data nibbles [$F $F $E $F $F $F] and Checksum $E, and Data nibbles [$F $F $F $E $E $F] and Checksum $F).

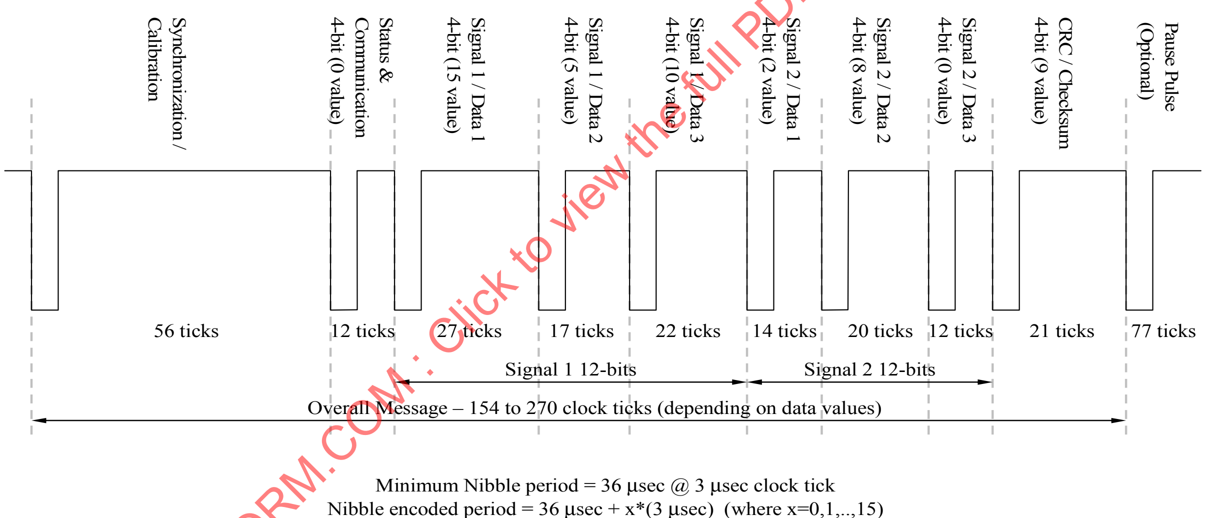


FIGURE 5.2.1-1 – EXAMPLE ENCODING SCHEME FOR TWO 12 BIT SIGNALS

Signals conveyed using the Data nibbles are also referred to as “Fast Channel” signals with this specification.

5.2.2 Transmission Properties of Calibration/Synchronization Pulse

- Nominal pulse period is 56 clock ticks.
- More than 4 clock ticks driven low time (all remaining clock ticks driven high).
- Actual period measured by receiving module to correct for transmitter clock variation.

5.2.3 Transmission Properties of Nibble Pulse

- Minimum pulse period is 12 clock ticks.
- More than 4 clock ticks driven low time (all remaining clock ticks driven high).
- Each nibble count is 1 clock tick (0 – 15 counts ⇒ 0 – 45 µs at a 3 µs clock tick).
- Minimum nibble pulse period (transmission value of 0) = 12 clock ticks (36 µs at a 3 µs clock tick).
- Maximum nibble pulse period (transmission value of 15) = 12 + 15 = 27 clock ticks (36 + 45 = 81 µs at a 3 µs clock tick).

See Figures 5.2.3-1 and 2 for pictorial representation of some nibble properties.

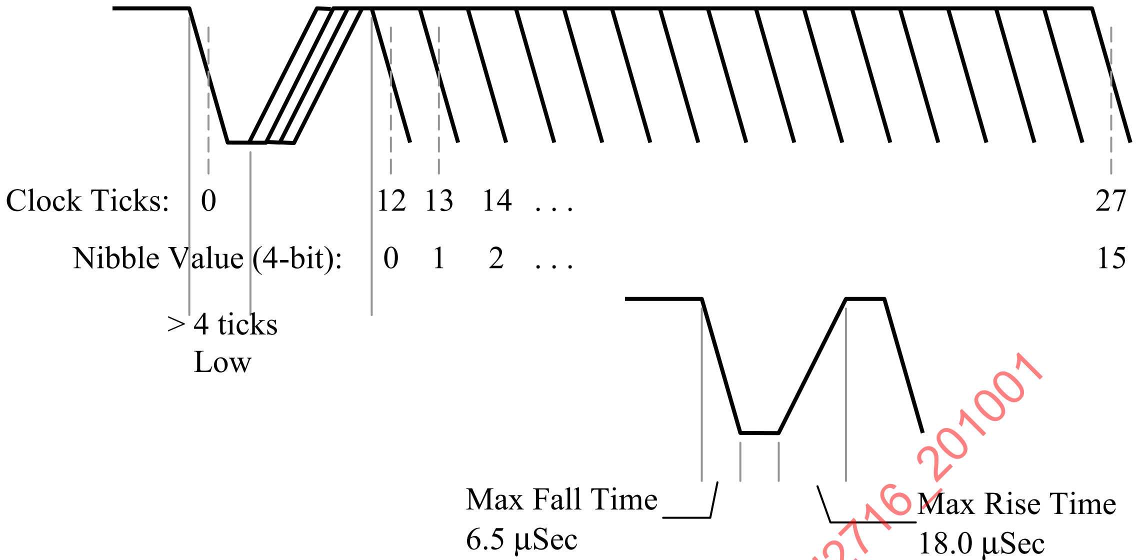


FIGURE 5.2.3-1 – EXAMPLE NOMINAL NIBBLE TIMES

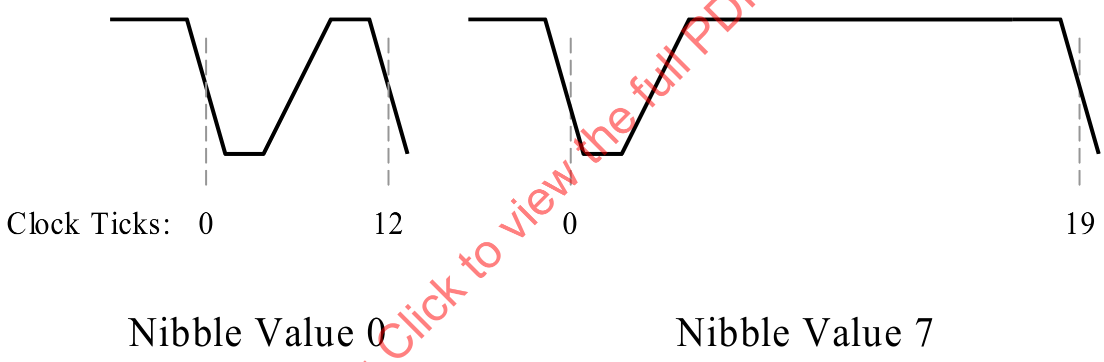


FIGURE 5.2.3-2 – CONTINUED EXAMPLE NIBBLE VALUES

5.2.4 Status and Communication Nibble

This nibble is reserved to enable the sensor to transmit miscellaneous information such as part numbers or error code information. The nibble is defined in the following table:

TABLE 5.2.4.1-1 – STATUS AND COMMUNICATION NIBBLE DESCRIPTION

Bit Number	Bit Function
0 (least significant)	Reserved for specific application
1	Reserved for specific application
2	Serial Data message bits
3 (most significant)	Message start = 1, otherwise = 0 or Serial data message bits

Note that the Status and Communication Nibble is not included in the frame CRC calculation and therefore can have a higher occurrence of non-detected errors.

Bits 2 and 3 define a transmitter optional serial message channel which can be implemented either as a short serial message format or an enhanced serial message format as specified below. SENT receivers shall support both the short serial message format as well as the enhanced serial message format.

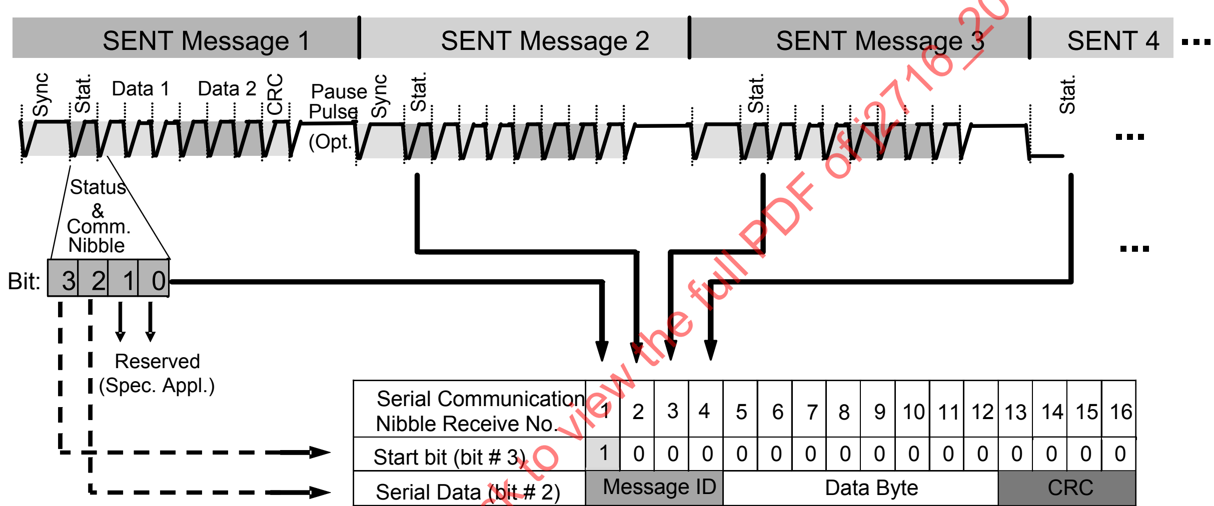
Signals conveyed using the serial message bits are also referred to as “Slow Channel” signals with this specification.

5.2.4.1 Short Serial Message Format

Serial data is transmitted (bit by bit) in bit 2 (of the Status and Communication nibble) of consecutive messages from the transmitter. Serial data will be communicated in a 16-bit sequence as shown in Figure 5.2.4.1-1. The starting bit of a serial message is indicated by a "1" in bit 3 of the Status and Communication nibble. The next 15 received frames must contain a value of "0" in this same bit 3 position, as shown in Figure 5.2.4.1-1. All 16 frames must be successfully received (no errors, calibration pulse variation, data nibble CRC error, etc.) for the serial value to be received (Figure 5.2.4.1-1).

The 16-bit message consists of a 4 bit Message ID nibble, 2 nibbles (1 byte) of data, and a CRC checksum nibble. The CRC checksum is derived for the Message ID and 2 data nibbles and is the same checksum algorithm as used to calculate the SENT CRC nibble (see 5.4). The Message ID is used to identify the type of data being communicated in the Data Byte. Actual Serial Data message IDs and data values are application specific.

All data transmitted in the Serial Data Bit (bit #2) is sent in the order Most Significant Bit to Least Significant Bit.



One serial message is composed of 16 SENT consecutive error-fee messages.

FIGURE 5.2.4.1-1 – CONSTRUCTION OF SHORT SERIAL DATA MESSAGE FROM 16 SENT MESSAGES

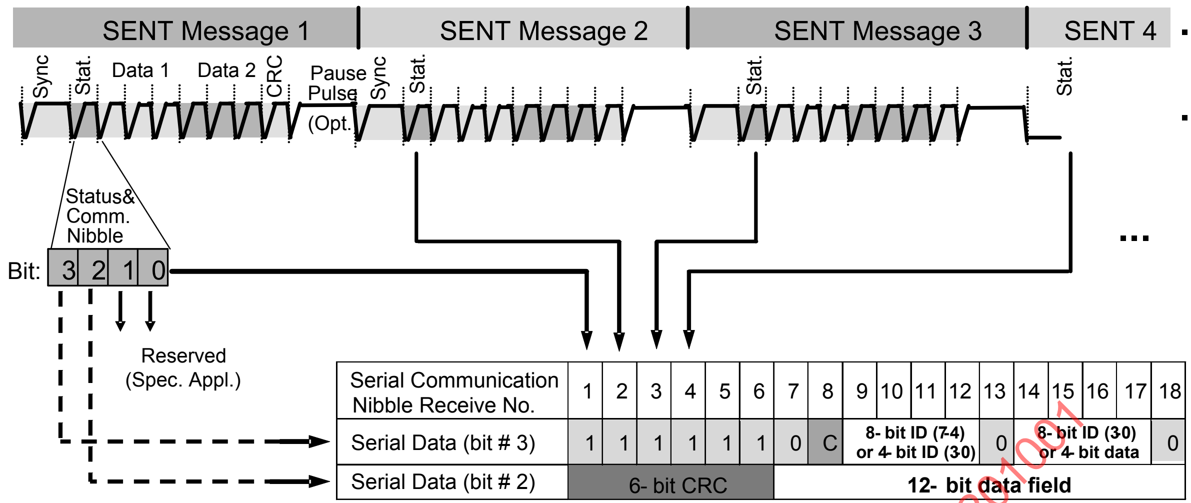
5.2.4.2 Enhanced Serial Message Format

An optional enhanced serial message format can be used by sensors, which require a serial communication channel with a larger data field and a larger set of message IDs. If the enhanced serial message channel is used, serial data is transmitted in bit #2 and bit #3 of the status and communication nibble. A serial message frame stretches over 18 consecutive SENT data messages from the transmitter as shown in Figure 5.2.4.2-1. All 18 frames must be successfully received (no errors, calibration pulse variation, data nibble CRC error, etc.) for the serial value to be received.

The frame start of a serial message is indicated by the unique pattern "01111110" in bit 3 of the status and communication nibble. The first "1" in a series of six ones (after a "0") indicates the first nibble of a serial message frame. Serial data bit #3 of serial communication nibbles 1 – 6 are set to "1". Serial data bit #3 of serial communication nibbles 7, 13 and 18 are set to "0".

The serial message frame contains 21 bits of payload data. Two different configurations can be chosen determined by the configuration bit (serial data bit #3, serial communication nibble No. 8):

- 12-bit data and 8-bit message ID (configuration bit = 0)
- 16-bit data and 4-bit message ID (configuration bit = 1)



One serial message is composed of 18 SENT consecutive error-fee messages.

FIGURE 5.2.4.2-1 – CONSTRUCTION OF ENHANCED SERIAL DATA MESSAGE FROM 18 SENT MESSAGES

All data (data field, message ID and CRC) that is transmitted in the serial message channel is sent in the order MSB (most significant bit) to LSB (least significant bit). The mapping and the order of the data bits, the message ID, the configuration bit and the CRC is detailed in Figure 5.2.4.2-2 for the configuration 12-bit data + 8-bit ID and in 5.2.4.2-3 for the configuration 16-bit data and 4-bit ID.

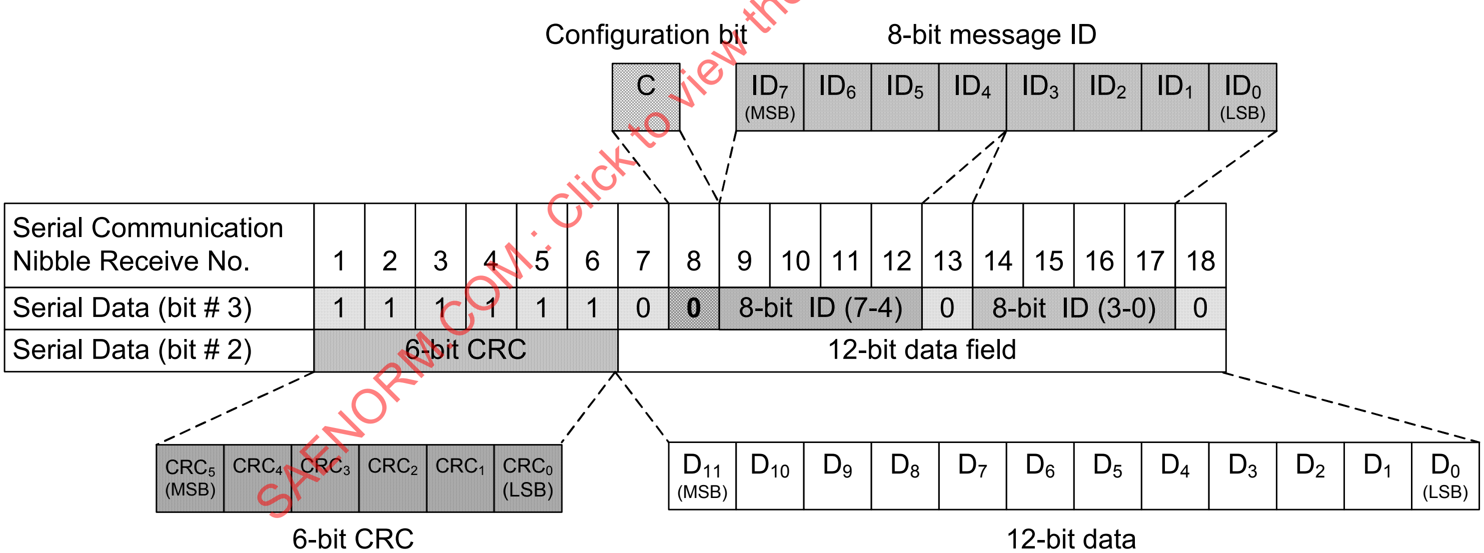


FIGURE 5.2.4.2-2 - ENHANCED SERIAL MESSAGE FORMAT WITH 12-BIT DATA FIELD AND 8-BIT MESSAGE ID

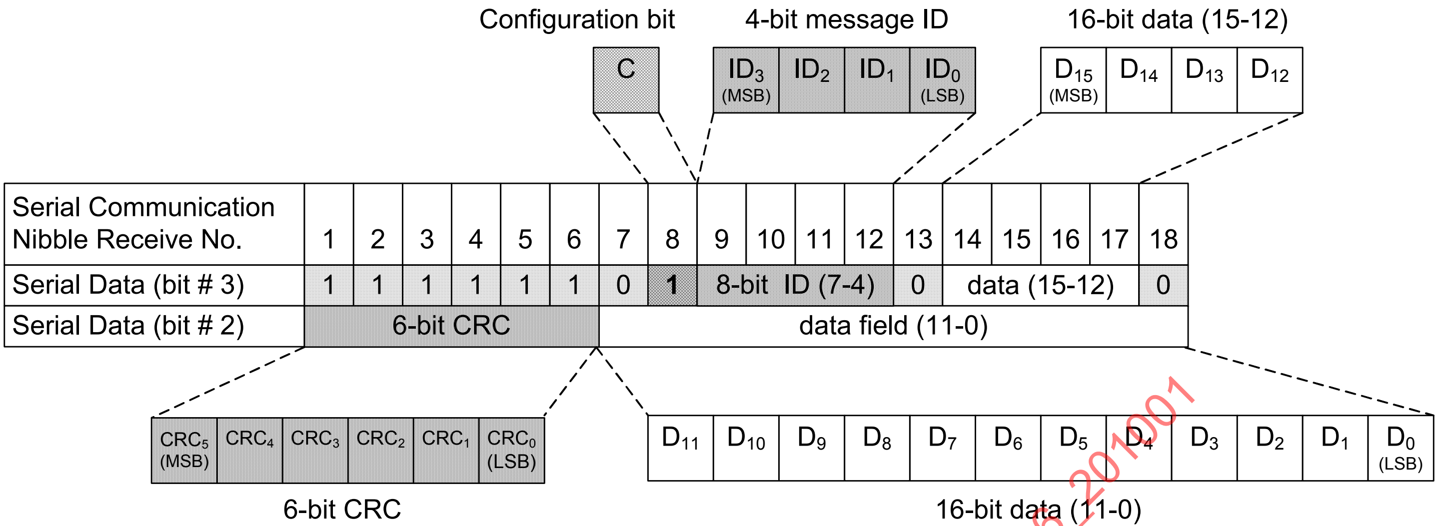


FIGURE 5.2.4.2-3 - ENHANCED SERIAL MESSAGE FORMAT WITH 16-BIT DATA FIELD AND 4-BIT MESSAGE ID

5.2.4.3 Enhanced Serial Message Format CRC

This CRC-value is computed as a function of the contents of Serial data message bits #2 and #3 for frames 7-18 (the 12-bit data field, the 8-bit message ID, the configuration bit and “0” bits 7, 13 and 18). For purposes of the CRC calculation, the bits shall be ordered: $\boldsymbol{m}$ = [Frame 7 bit#2, Frame 7 bit #3, Frame 8 bit #2, Frame 8 bit #3 .. Frame 18 bit #2, Frame 18, bit #3], see Figure 5.2.4.3-1. These bits contribute to the message data $\boldsymbol{m} = [m_0 \quad m_1 \quad m_2 \ \ldots\ldots \ m_{21} \quad m_{22} \quad m_{23}]$. Bit m_0 (which corresponds to frame bit D_{11} is the first received bit that is read-in for CRC generation, as illustrated in the lower half of Figure 5.2.4.3-1.

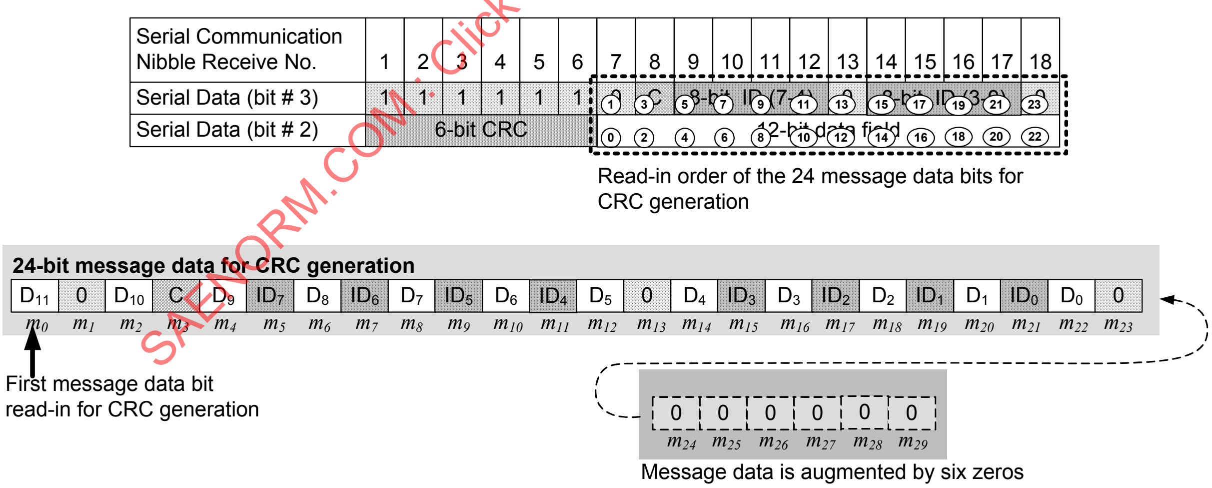


FIGURE 5.2.4.3-1 - ORDER OF THE MESSAGE BITS, 24-BIT MESSAGE USED FOR CRC GENERATION

The encoding is defined by the generating polynomial.

$G(x) = x^6+x^4+x^3+1$

with seed value 010101 (0x15 hex, 21 dec). For CRC generation, the message will be augmented by six zeros $\boldsymbol{m}_{crc} = [m_0 \quad m_1 \quad m_2 \ \ldots\ldots \ m_{21} \quad m_{22} \quad m_{23} \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]$.

The 6-bit CRC polynomial $x^6+x^4+x^3+1$ allows to detect all 1- bit, 2-bit, 3-bit, 5-bit errors. The number of undetected 4-bit errors depends on the number of message data bits as shown in the Table 5.2.4.3-1.

TABLE 5.2.4.3-1 – UNDETECTED 3 AND 4 BIT ERRORS

Message Data	Number of undetected 3-bit errors	Number of undetected 4-bit errors
24 bit	0	365
24 bit + error detection of frame bits 7, 13 and 18	0	208

The number of possible 4-bit error patterns is $\binom{24}{4}$. The percentage of undetected 4-bit errors is approximately 3.4%.

The three serial data bits #3 of frames No. 7, 13 and 18 are known to be zero. If any of the three serial data bits #3 of nibbles No. 7, 13 and 18 differs from zero, the frame shall be considered as erroneous. This reduces the number of undetected 4-bit errors from 365 to 208.

The CRC checksum can be implemented via a bit-wise exclusive OR with a 64 array lookup. The checksum is determined by reading-in 6-bit groups (in decimal representation) of the 24-bit message data in sequence, and then checksumming the result with an extra zero value (augmentation by six 0-bits). An example MATLAB implementation is:

```
  % Table-based CRC generation with Matlab
  % 24-bit message data
  % data = 4 x 6-bit  (Attention: Difference to 4-bit nibbles)

  % CRC table for poly = 0x59  (x^6+x^4+x^3+1)
  % Seed 0x15  (21)
    crc6_table = [ ...
   0  25  50  43  61  36  15  22  35  58  17   8  30   7  44  53 ...
  31   6  45  52  34  59  16   9  60  37  14  23   1  24  51  42 ...
  62  39  12  21   3  26  49  40  29   4  47  54  32  57  18  11 ...
  33  56  19  10  28   5  46  55   2  27  48  41  63  38  13  20 ];

CheckSum64 = 21; % initialize checksum
for I=1:4
  CheckSum64 = bitxor(uint8(data(I)), uint8(crc6_table(CheckSum64+1)));
end
% checksum with an extra "0" value (message is augmented by six zeros)
CheckSum64 = bitxor(uint8(0), uint8(crc6_table(CheckSum64+1)));
```

Examples of the CRC computation are given in Appendix B.2.

5.2.5 Checksum Nibble

See 5.4.

5.2.6 Pause Pulse (Optional)

The SENT transmission may optionally contain an extra fill pulse which is transmitted after the checksum nibble. For example, this pulse can be used to create a SENT transmission with a constant number of clock ticks. If implemented, the pause pulse shall have the following properties:

- Minimum Length 12 ticks (equivalent to a nibble with 0 value)
- Maximum Length 768 ticks (3 * 256)

For a message with 6 data nibbles, the minimum constant length SENT message would be 282 ticks (assuming correct checksum calculation) for a pause pulses range of 12 ticks to 128 ticks. If a maximum message length of less than 1ms is desired then the transmitter clock tolerance must be decreased to (-20%, +18%) (see Table 6.2.1-1).

5.3 Transmission and Reception of Message

5.3.1 Transmission of Message

Each specific implementation of the encoding scheme (e.g. throttle sensors, pedal sensors, mass air sensors, etc.) shall have a defined sequence, a calibration pulse followed by a constant number of nibbles (and possibly a pause pulse). The transmitting module shall send the defined sequence repeatedly.

5.3.2 Adjustment of Received Message Nibble Lengths

The ECU shall receive the encoded signal by monitoring the time between falling edges (the pulse period). The measurement of a pulse period equal to the calibration pulse ±20% shall signal the start of a new message. The actual period of the calibration pulse received shall be used to adjust the period of the succeeding nibble pulses within the message. This calibration pulse is required to correct for clock frequency variation in the sensor/transmitting device.

The ratio between the measured calibration pulse period and the nominal (56 clock tick) period shall be calculated. Each of the message's remaining measured (nibble) pulse periods is then divided by this ratio to correct them back to the equivalent nominal period. These corrected periods then have the 12 clock tick minimum period subtracted and the resulting data length period divided by the nominal clock tick period and rounded to an integer value to obtain the data nibble value. The process is summarized by the following algorithm (assuming a 3 µs nominal clock tick):

Rcal = Measured Calibration pulse period/168 µs
Data Value N = Round[(Measure pulse period N/Rcal – 36 µs)/3 µs]

This section is intended to describe the theory of how data nibbles are to be interpreted by a receiver. Other methods which achieve this same end result are also acceptable.

5.3.3 Received Message Diagnostics

The receiver module shall monitor the message for the following conditions. If any of the below conditions are met, the receiver module shall declare that a message error has occurred and ignore the entire message. Note, not all diagnostics need to be run for each individual message if the message has already been deemed to be in error by a previous diagnostic.

- Calibration pulse length < 56 clock ticks – 25% or > 56 clock ticks + 25%.
- Not the expected number of falling edges between calibration pulses. (Message length is pre-defined by each sensor device)
- Checksum error.
- Any nibble data values measured as < 0 or > 15.
- One of the following two conditions
    - Successive calibration pulses differ by > +1.5625% (1/64) or < -1.5625%. See section 5.3.3.1 for more detail
    - (for pause pulse with fixed message length only) Ratio of calibration pulse to message length varies by >1.5625% or <-1.5625%. To minimize message latency, this diagnostic can be used as the receiver does not need to wait for the next calibration pulse to diagnose the current received frame. It is only recommended for precisely controlled constant message length.

Any of the errors above shall also cause the receiver to begin searching for a valid calibration pulse to re-synchronize reception to the transmitting device start of message. The diagnostics above will allow the reception of message with ±25% timing range. However, only systems with a maximum ±20% timing range will be certified as meeting the SENT requirements.

For systems with a pause pulse, during synchronization or re-synchronization of reception, if calibration pulses are detected one immediately following the other, the first calibration pulse shall be ignored as it may be a pause pulse with duration matching the calibration pulse range.

5.3.3.1 Successive Calibration Pulses

The diagnostic for detecting successive calibration pulses differing by > 1.5625% shall be implemented by one of two methods. Options are described with reference to Fig. 5.3.3.1-1 where the calibration pulse of Frame n differs from Frames n-1, n+1 and n+2 by > 1.5625% threshold.

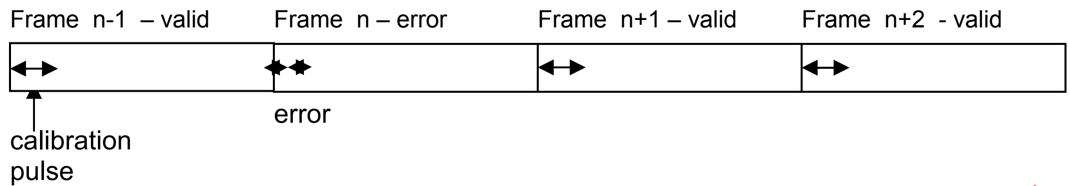


FIGURE 5.3.3.1-1 - ERROR PATTERN FOR SUCCESSIVE CALIBRATION PULSE DETECTION.

Preferred Option:

The calibration pulse of current frame is compared to the calibration pulse of the preceding frame. If they differ by > the threshold 1.5625%, the preceding frame is declared to be bad and ignored. No special initialization or resynchronization is required.

i. Calibration pulse n-1 is compared to calibration pulse n and the entire message of Frame n-1 is declared to be bad even though the calibration pulse is correct.

ii. Calibration pulse n is compared to calibration pulse n+1 and the entire message of Frame n is declared to be bad.

iii. Calibration pulse n+1 is compared to calibration pulse n+2. Message n+1 passes the test.

Advantages of the Preferred Option

- “Too many nibbles between calibration pulses” can be detected
- Clock variation affecting calibration pulse and immediately preceding or succeeding nibbles can be detected.

Disadvantages of the Preferred Option

- Potentially, a valid frame (frame n-1) could be declared to be bad
- There is an extra latency of the length of the calibration pulse in processing the message in the receiver (see Figure 5.3.3.1-2).

Option 2 (should only be used if extra latency to process second calibration pulse cannot be tolerated)

The calibration pulse of current frame is compared to the calibration pulse of the last valid preceding frame (i.e. frame with no errors). If they differ by > the threshold 1.5625%, the frame is declared to be bad and ignored.

Initialization: The first calibration pulse shall be considered valid unless the message frame contains other errors.

Resynchronization: On the third successive calibration pulse error, the current calibration pulse value shall be considered as valid and the message accepted unless the message frame contains other errors.

i. Calibration pulse n is compared to calibration pulse n-1 and the entire message of Frame n is declared to be bad.

ii. Calibration pulse n+1 is compared to calibration pulse n-1 and the entire message of Frame n+1 is declared to be valid.

iii. Calibration pulse n+2 is compared to calibration pulse n+1. Message n+2 passes the test.

Advantages of Option 2

- Message processing can be completed within 1 ms worst case timing

Disadvantages of the Option 2

- “Too many nibbles between calibration pulses” cannot be detected as the next calibration pulse has not been received.
- Clock variation affecting calibration pulse and immediately succeeding nibbles cannot be detected by calibration pulse comparison.

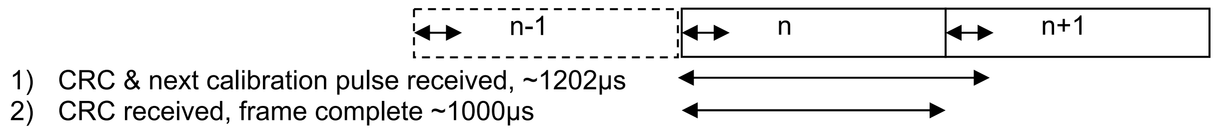


FIGURE 5.3.3.1-2 - SUCCESSIVE CALIBRATION PULSE DETECTION.

5.3.4 Reset

Should the transmitting module reset for any reason, it shall start transmitting a new message immediately following its initialization procedure. The output signal shall be held in the high state until initialization is completed.

Application-specific sensors, which use an initialization message (data nibbles set to zero – this value is excluded from the possible measurement data values) can start transmitting after a reset in two phases: If the SENT interface of the transmitting module is initialized after a reset, while the measurement unit of the transmitting module is still initializing, the initialization message is transmitted until valid measurement values are available.

5.4 Checksum Nibble Details

The Checksum nibble is a 4 bit CRC of the Data nibbles only. The Status and Communication Nibble is not included in the CRC calculation.

The CRC is calculated using polynomial x^4 + x^3 + x^2 + 1 with seed value of 0101.

5.4.1 Errors Detected and Not Detected by Checksum

The following bit flip errors are detectable using the polynomial:

1. All single bit errors.
2. All odd number of nonconsecutive bit errors.
3. All single burst errors of length ≤ 4.
4. 87.5% of single burst errors of length = 5.
5. 93.75% of single burst errors of length > 5.

The fault mode of most concern for the signal encoding scheme is a shifted falling edge which would cause one nibble to appear to be a longer (shorter) period followed by a nibble with a shorter (longer) period than intended by the transmitting device. The CRC detects all cases of 1, 2, 4, 8, 9, 10, 12, 13, 14 and 15 count shifts over two nibbles.

The CRC polynomial will not detect all cases of 3, 5, 6, 7, 11 count shifts. These undetectable patterns are listed in Table 5.4.1-1. For example, row 3 of Table 3 has error pattern 101 followed by 11. If nibble 1 was 4 (100) and nibble 2 0 (000), after the bit flips nibble 1 becomes 1 (001) and nibble 2 becomes 3 (011). Nibble 1 has shifted by –3 and nibble 2 by +3. It is assumed that the risk associated with not detecting these types of faults is acceptable given the high update rate available to the encoding scheme.

TABLE 5.4.1-1 - BIT FLIP PATTERNS OVER TWO NIBBLES
NOT DETECTABLE USING THE CRC POLYNOMIAL

Nibble 1 Error Pattern		Nibble 2 Error Pattern	
8	1000	1	1
13	1101	2	10
5	101	3	11
7	111	4	100
15	1111	5	101
10	1010	6	110

2	10	7	111
14	1110	8	1000
6	110	9	1001
3	11	10	1010
11	1011	11	1011
9	1001	12	1100
1	1	13	1101
4	100	14	1110
12	1100	15	1111

Table 5.4.1-2 lists the missed detection rate for the shifted edge failure resulting in a longer followed by a correspondingly equally shortened pulse. Table 5.4.1-3 lists the missed detection rate for the same situation except that the shifted edge results in an offset of one in the change of the shortened versus the longer pulse.

TABLE 5.4.1-2 - CHECKSUM MISSED DETECTION RATE, EDGE SHIFT BETWEEN TWO NIBBLES (VALID FRAMES ONLY, RECOMMENDED IMPLEMENTATION)

Shift Nibble X	**Shift Nibble X+1**	**Not detected [%]**
-15	15	0.00
-14	14	0.00
-13	13	0.00
-12	12	0.00
-11	11	16.00
-10	10	0.00
-9	9	8.16
-8	8	0.00
-7	7	4.94
-6	6	16.00
-5	5	6.61
-4	4	0.00
-3	**3**	**11.83**
-2	**2**	**0.00**
-1	**1**	**0.00**
1	**-1**	**0.00**
2	**-2**	**0.00**
3	**-3**	**11.83**
4	-4	0.00
5	-5	6.61
6	-6	16.00
7	-7	4.94
8	-8	0.00
9	-9	8.16
10	-10	0.00
11	-11	16.00
12	-12	0.00
13	-13	0.00
14	-14	0.00
15	-15	0.00

TABLE 5.4.1-3 - CHECKSUM MISSED DETECTION RATE, ASYMMETRICAL EDGE SHIFT OFFSET BY 1 BETWEEN TWO NIBBLES (VALID FRAMES ONLY, RECOMMENDED IMPLEMENTATION)

Shift Nibble X	Shift Nibble X+1	Not detected [%]
-14	15	0.00
-13	14	0.00
-12	13	33.33
-11	12	0.00
-10	11	0.00
-9	10	0.00
-8	9	0.00
-7	8	0.00
-6	7	17.78
-5	6	0.00
-4	5	3.03
-3	4	10.26
-2	**3**	**8.79**
-1	**2**	**0.00**
0	**1**	**0.00**
1	**0**	**0.00**
2	**-1**	**7.62**
3	**-2**	**8.79**
4	-3	2.56
5	-4	12.12
6	-5	0.00
7	-6	0.00
8	-7	0.00
9	-8	0.00
10	-9	0.00
11	-10	0.00
12	-11	20.00
13	-12	0.00
14	-13	0.00
15	-14	0.00
-15	14	0.00
-14	13	0.00
-13	12	0.00
-12	11	20.00
-11	10	0.00
-10	9	0.00
-9	8	0.00
-8	7	0.00
-7	6	0.00
-6	5	0.00
-5	4	12.12
-4	3	2.56
-3	**2**	**8.79**
-2	**1**	**7.62**
-1	**0**	**0.00**
0	**-1**	**0.00**

1	**-2**	**0.00**
2	**-3**	**8.79**
3	-4	10.26
4	-5	3.03
5	-6	0.00
6	-7	17.78
7	-8	0.00
8	-9	0.00
9	-10	0.00
10	-11	0.00
11	-12	0.00
12	-13	33.33
13	-14	0.00
14	-15	0.00

5.4.2 CRC Implementation

SENT receivers shall be capable of implementing both checksum implementations below but sensors should use the recommended implementation. The same 4-bit CRC implementation shall be used for both a per frame basis (i.e. checksum of all data nibbles) and for Short Serial Message Format checking.

5.4.2.1 Legacy Implementation (as in revision FEB2008 and older)

The CRC checksum can be implemented as a series of shift left by 4 (multiply by 16) followed by a 256 array lookup. An example MATLAB implementation is:

numNibbles is the number of nibbles to be checksummed
The data array contains the nibble to be checksummed and the 256 table is given below in MATLAB form:

```
% CRC 4 nibble lookup table
CRC4Table= [ ...
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 ...
13 12 15 14 9 8 11 10 5 4 7 6 1 0 3 2 ...
7 6 5 4 3 2 1 0 15 14 13 12 11 10 9 8 ...
10 11 8 9 14 15 12 13 2 3 0 1 6 7 4 5 ...
14 15 12 13 10 11 8 9 6 7 4 5 2 3 0 1 ...
3 2 1 0 7 6 5 4 11 10 9 8 15 14 13 12 ...
9 8 11 10 13 12 15 14 1 0 3 2 5 4 7 6 ...
4 5 6 7 0 1 2 3 12 13 14 15 8 9 10 11 ...
1 0 3 2 5 4 7 6 9 8 11 10 13 12 15 14 ...
12 13 14 15 8 9 10 11 4 5 6 7 0 1 2 3 ...
6 7 4 5 2 3 0 1 14 15 12 13 10 11 8 9 ...
11 10 9 8 15 14 13 12 3 2 1 0 7 6 5 4 ...
15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0 ...
2 3 0 1 6 7 4 5 10 11 8 9 14 15 12 13 ...
8 9 10 11 12 13 14 15 0 1 2 3 4 5 6 7 ...
5 4 7 6 1 0 3 2 13 12 15 14 9 8 11 10 ...
];

CheckSum = 5; % initialize checksum
for I=1:numNibbles
   tempCS = data(I)+CheckSum*16;
   CheckSum = CRC4Table(tempCS+1);
end
```

This implementation is included for backwards compatibility. Based on valid patterns, it is subject to a 42 % missed detection rate of edge shifts between the final data nibble and the checksum nibble and is not recommended.

5.4.2.2 Recommended Implementation

The recommended CRC calculation utilizes the same seed value and polynomial as the legacy calculation but also augments the message data with an extra 4 zero bits in the CRC calculation.

Example implementations are given below. Other implementations are possible. For example, the CRC can also be implemented as a series of bit-wise XOR and shift operations or a reduced sized table can be used. Example checksum values are given in Appendix B.

5.4.2.2.1 Implementation using 256 Element Array

The CRC checksum can be implemented as a series of shift left by 4 (multiply by 16) followed by a 256 element array lookup. The checksum is determined by using all data nibbles in sequence and then checksumming the result with an extra zero value. An example MATLAB implementation is (same CRC4Table as in section 5.4.2.1):

```
CheckSum = 5; % initialize checksum
for I=1:numNibbles
   tempCS = data(I)+CheckSum*16;
   CheckSum = CRC4Table(tempCS+1);
end
% checksum with an extra “0” value
tempCS = CheckSum*16;
CheckSum = CRC4Table(tempCS+1);
```

5.4.2.2.2 Implementation using 16 Element Array

The CRC checksum can be implemented as a bit-wise exclusive OR with a 16 element array lookup. The checksum is determined by using all data nibbles in sequence and then checksumming the result with an extra zero value. An example MATLAB implementation is:

```
%CRC table for poly = 0xd
crc4_table = [ ...
   0 13 7 10 14 3 9 4 1 12 6 11 15 2 8 5 ];

CheckSum16 = 5; % initialize checksum
for I=1:numNibbles
  CheckSum16 = bitxor(uint8(data(I)), uint8(crc4_table(CheckSum16+1)));
end
% checksum with an extra “0” value
CheckSum16 = bitxor(uint8(0), uint8(crc4_table(CheckSum16+1)));
```

6. SENT PHYSICAL LAYER OPERATION

The physical layer is responsible for providing a method of transferring digital data encoded as time between two falling edges of a signal through the communication medium. This results in repeatable and time accurate switching of the input circuit of the physical layer interface which consists of power, ground and signal wires.

6.1 Normal Communication Mode and Transmission Rate

Transmission bit rate is variable depending on the clock tick period, data values sent and the transmitter nominal clock variance and +20% clock tolerance. The longest transmission time for 6 Data nibbles is 270 clock ticks or 972 µs at a 3 µs clock tick period, this results in a worst case transmission rate of ~24.7 kBits/s. Similarly, the shortest valid 6 Data nibble message is 154 clock ticks which at –20% clock tolerance results in a transmission rate of ~64.9 kBits/sec. These calculations ignore the contribution made by Serial data transmission (see 5.2.2).

6.2 Clock Tolerance

6.2.1 Transmitter–Receiver Communications

Table 6.2.1-1 lists the timing and resolution requirements for the transmitting and receiving modules. To avoid requiring a high cost oscillator in the transmitter, the transmitter clock frequency variation is allowed to be large. Requirements for Clock Drift Error and Jitter at intermediate clock tick periods shall be linearly interpolated between the minimum and maximum clock tick periods in Table 6.2.1-1.

TABLE 6.2.1-1 – COMMUNICATION CLOCK TOLERANCE

Device Type	Parameter	Clock Tolerance
Transmitter	Clock Accuracy	≤ ±20% no pause pulse > -20%, < + 18%, pause pulse (optional)
Transmitter	Clock Jitter and Drift Error	≤ 0.05 µs variation of maximum nibble time compared to the expected time derived from the calibration pulse time at a 3 µs clock tick ≤ 0.25 µs variation of maximum nibble time compared to the expected time derived from the calibration pulse time at a 10 µs clock tick*
Transmitter	Clock Tick Period Ranges	3 to 90 µs nominal*
Receiver	Clock Drift Error (excluding Clock Jitter)	≤ 0.05 µs variation of maximum nibble time compared to the expected time derived from the calibration pulse time at a 3 µs clock tick ≤ 0.25 µs variation of maximum nibble time compared to the expected time derived from the calibration pulse time at a 10 µs clock tick*
Receiver	Clock Jitter (including sampling quantization)	≤ 0.10 µs variation of maximum nibble time compared to the expected time derived from the calibration pulse time at a 3 µs clock tick ≤ 0.50 µs variation of maximum nibble time compared to the expected time derived from the calibration pulse time at a 10 µs clock tick*

* For clock tick times greater than 10 µs, transmitter "Clock Jitter and Drift Error" and receiver “Clock Drift Error” and "Clock Jitter" can be increased linearly proportionally to the 10µs clock tick values (see Figure 6.2.1-1).

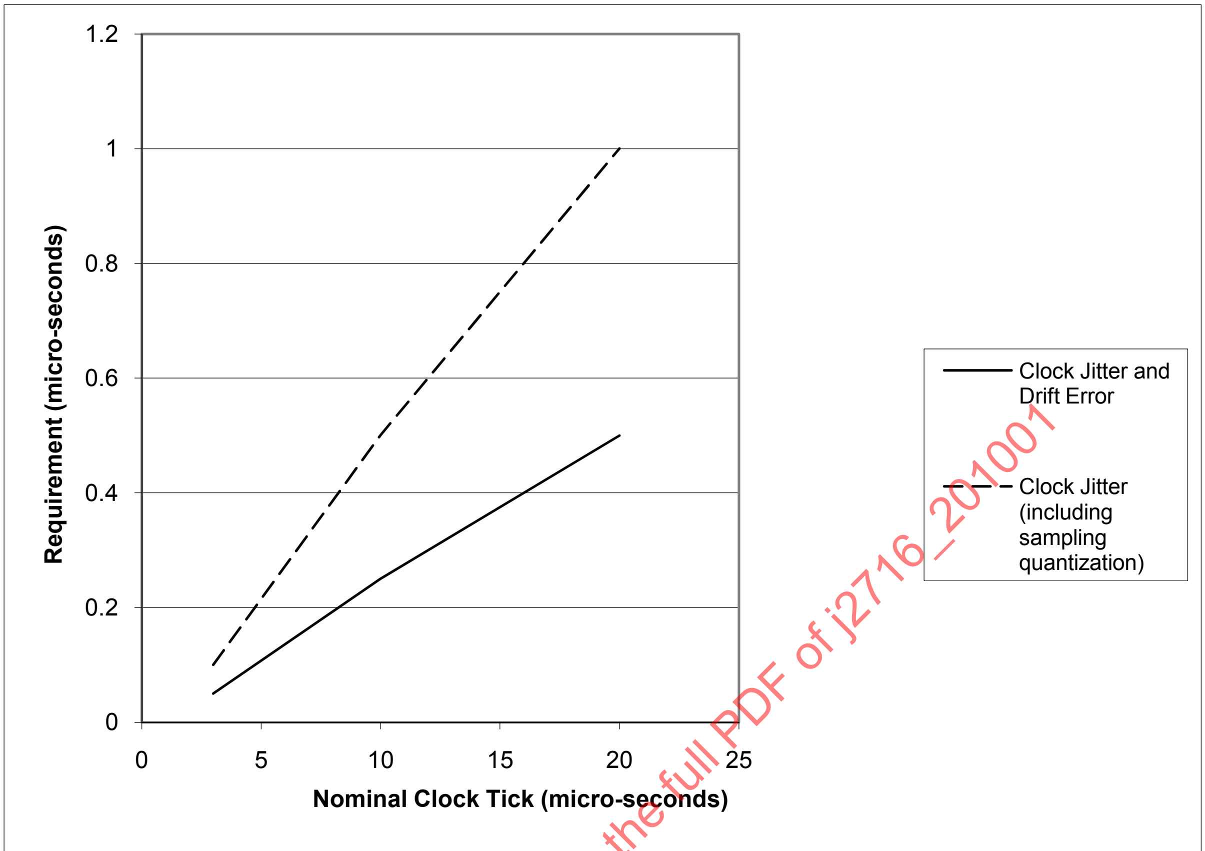


FIGURE 6.2.1-1 – CLOCK DRIFT ERROR AND JITTER REQUIREMENTS VERSUS NOMINAL CLOCK TICK

6.3 Electrical Interface Requirements

The SENT signal can be seen as a nominal 5 V square wave signal, but for low radiated emissions, signal shaping is required. To minimize ground and supply offset effects, the receiving device shall provide a regulated 5 V supply and ground reference to the transmitting device as specified below. This signal is intended to operate in automotive under-hood control system applications. The driver and receiver shall be protected from shorts to ground or vehicle voltages and various transient pulses as required below and by the specific vehicle EMC requirements.

Figures 6.3-1 and 6.3-2 show two alternative receiver circuit topologies. One of the two shall be used; however, Figure 6.3-1 is included for backwards compatibility with specification version FEB2008 and is not recommended for new implementations. Figure 6.3-2 represents the recommended approach for new implementations.

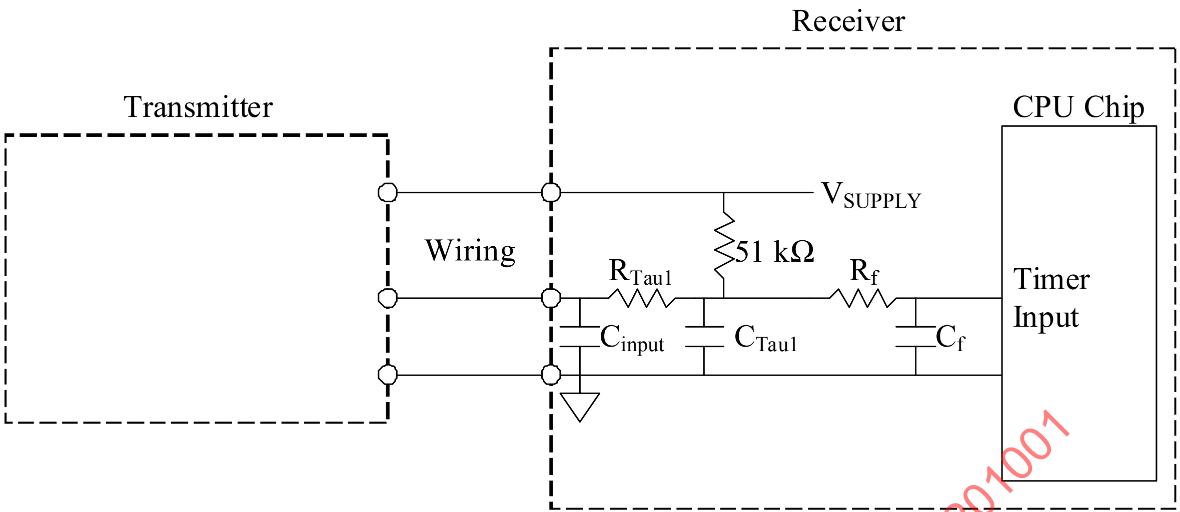


FIGURE 6.3-1 – LEGACY SENT RECEIVER INTERFACE CIRCUIT TOPOLOGY

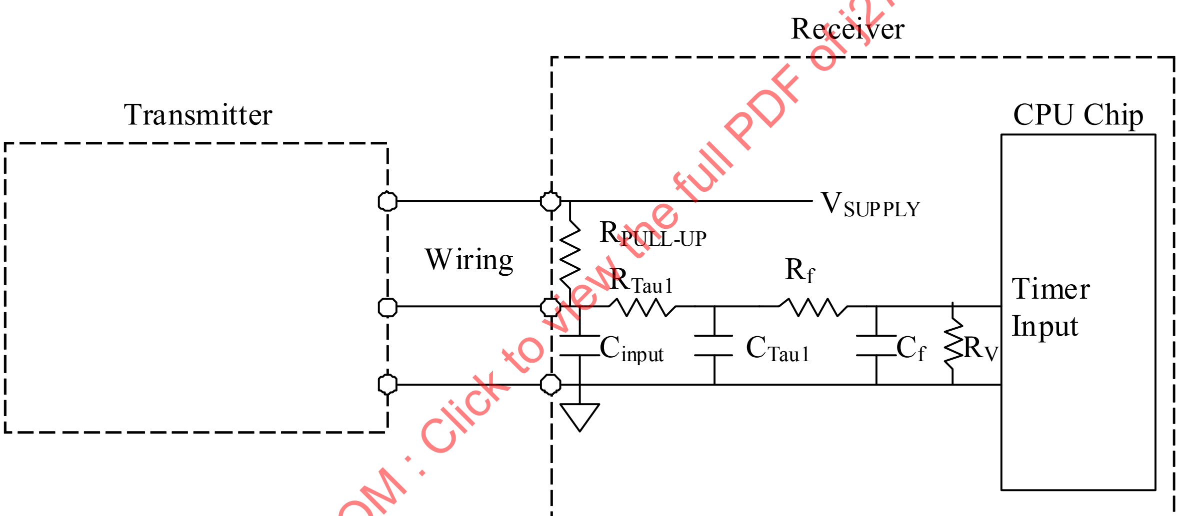


FIGURE 6.3-2 – RECOMMENDED SENT SYSTEM INTERFACE CIRCUIT TOPOLOGY

Figures 6.3-3 and 6.3-4 illustrate possible equivalent circuits for a SENT transmitter and receiver. The Transmitter portion of these circuits are examples only and should not be taken as a direct implementation requirement. All interface requirements in this document shall be met whether the implementation follows the example circuit topology or not.

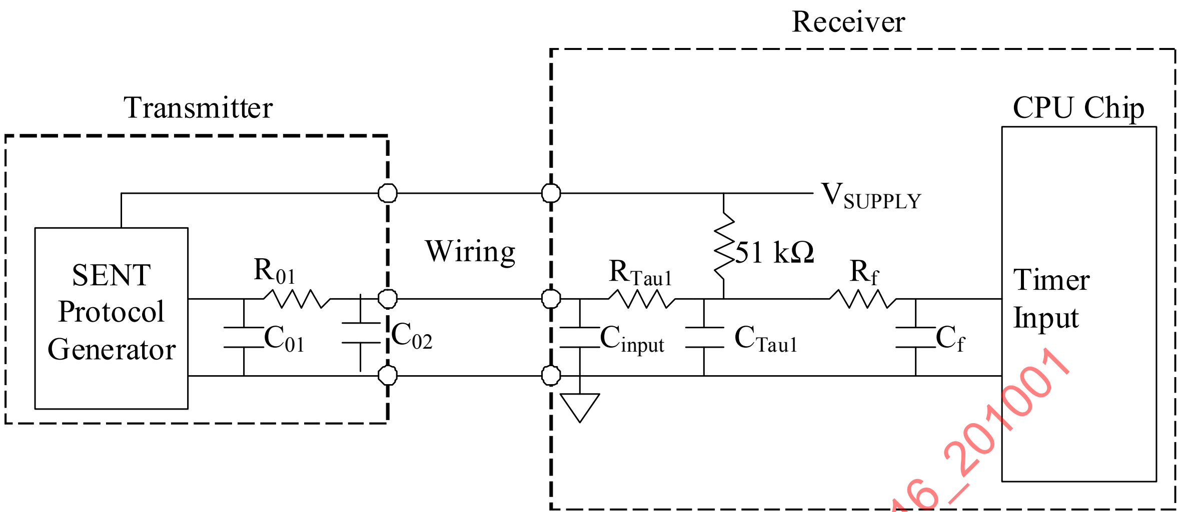


FIGURE 6.3-3 – EXAMPLE LEGACY SENT SYSTEM INTERFACE CIRCUIT TOPOLOGY

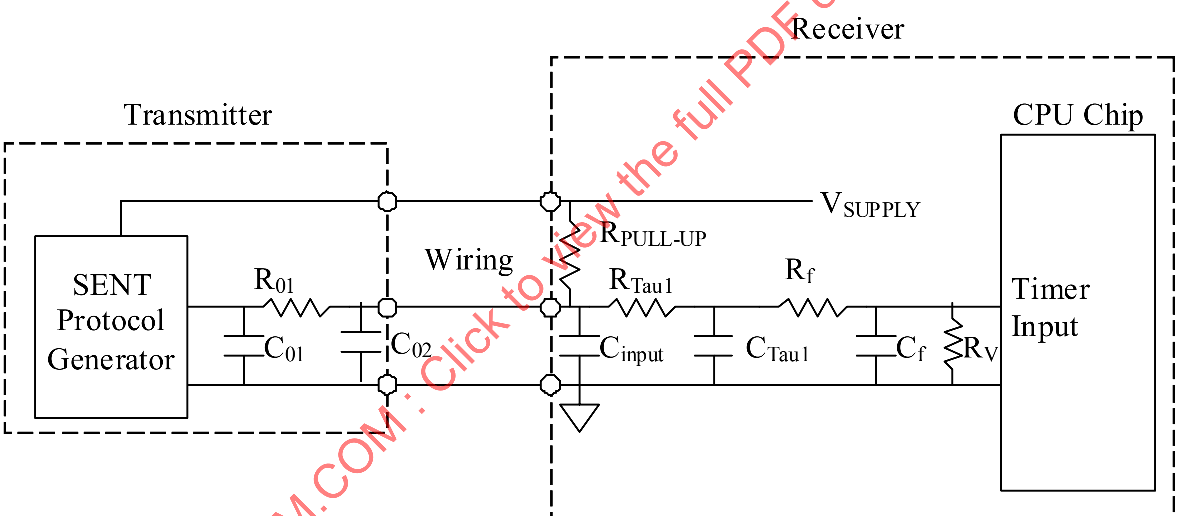


FIGURE 6.3-4 – EXAMPLE RECOMMENDED SENT SYSTEM INTERFACE CIRCUIT TOPOLOGY

6.3.1 Transmitter Driver Requirements

The transmitting device shall provide a driver with a configuration and technology suitable for the automotive environment. The driver shall ensure that the signal rise and fall time requirements are met when driving into the receiver passive load defined in the next section. The transmitter shall be protected from damage due to voltage or current conditions on the output signal outside those defined in Table 6.3.1-1 (e.g., shorts to power or ground). Any condition which could result in damage to the transmitter shall cause the transmitter to turn its driver Off to limit current flow and prevent damage. The requirements in Table 6.3.1-1 shall be met over the entire transmitter environmental requirement range.

In addition an EMC filter consisting of a capacitor followed by a resistor in series with the output pin is recommended to attenuate RF energy coupled on the external signal line. See Figure 6.3-1. In order to meet radiated emission EMC requirements, it is expected that a “shaped” waveform (controlled slope and corner rounding) will need to be driven by the transmitter. Figure 6.3.1-1 illustrates an example shaped waveform (falling and rising edge) that could meet emissions requirements.

The transmitter shall meet the input threshold level at the receiver with maximum time constants of the input filters.

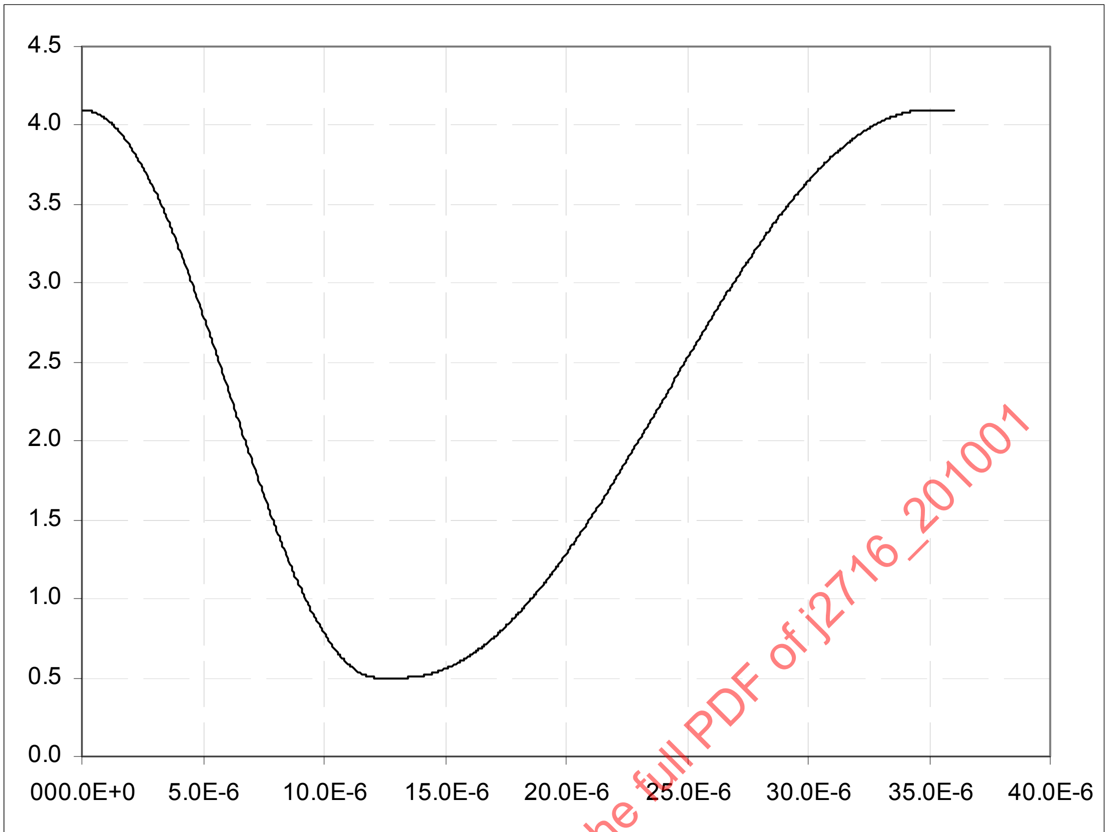


FIGURE 6.3.1-1 – EXAMPLE SENT SHAPED WAVEFORM TRANSMITTER OUTPUT

TABLE 6.3.1-1 – TRANSMITTER DRIVER REQUIREMENTS

Parameter			Limits (including component tolerances) Min	Max	Units	Test Conditions / Definitions (on wire)
a.	V_{OL}	=		0.5	V	Low state Voltage @ 0.1 mA DC load current
b.	V_{OH}	=	4.1		V	High state Voltage @ 0.1 mA DC load current
c.	I_{SUP}	=		20	mA	Average current consumption from Receiver supply over one message
d.	$I_{SUP-RIPPLE}$	=		9.0	mA	Peak-to-peak variation in supply current consumption
e.	T_{FALL}	=		6.5*	µs	From 3.8 V to 1.1 V
f.	T_{RISE}	=		18*	µs	From 1.1V to 3.8V
g.	ΔT_{FALL}	=		0.1*	µs	Edge to edge jitter with static environment for any pulse period
h.	T_{STABLE}	=	6**		µs	Signal stabilization time below V_{IL} (low signal) or above V_{IH} (high signal)

* For 3µs nominal clock tick including clock accuracy. For higher clock tick times these values can be increased proportionally.

** If "T_{FALL}", "T_{RISE}" or "ΔT_{FALL}" are increased, T_{STABLE} has to be increased by the same ratio as well.

6.3.2 Receiver Input Requirements

The Receiving device shall provide a resistive pull-up to the supply voltage, a controlled threshold digital receiver, and a timing channel (to measure pulse periods). The receiver shall meet the requirements of Table 6.3.2-1 over the entire Receiving device environmental requirement range.

The input shall include an EMC low-pass filter consisting of a 560 Ohm resistor followed by a 2.2 nF capacitor to attenuate RF energy coupled on the external signal line. See Figure 6.3-2 and Table 6.3.2-1. This filter should be implemented as close to the signal input pin as possible.

TABLE 6.3.2-1 – RECEIVER INPUT REQUIREMENTS

Parameter			Limits (including component tolerances) Min	Max	Units	Test Conditions / Definitions
a.	$R_{PULL-UP}$	=	10000	55000	Ohms	Input pull-up resistance
b.	C_{INPUT}	=		0.1	nF	Parasitic input capacitance and ESD protection
c.	V_{IL}	=	1.39		V	Input low state threshold range
d.	$V_{IL-DELTA}$	=	-50	50	mV	Maximum input low state threshold variation over 1 millisecond interval with supply Voltage constant
e.	V_{IH}	=		3.8	V	Input high state threshold range
f.	V_{HYST}	=	0.3		V	Input electrical hysteresis ($V_{HYST} = V_{IH} - V_{IL}$)
g.	Tau1	=	0.74	1.73	µs	Input filter time constant – first stage
h.	Tau2	=	0.6	1.4	µs	Input filter time constant – second stage determined by R_V, R_f and C_f
i.	R_{Tau1}		448	672	Ohms	560 +/- 20% overall tolerance must meet Tau1 requirement
j.	C_{Tau1}		1.54	2.86	nF	2.2 +/- 30% overall tolerance must meet Tau1 requirement
k.	R_f		4		kΩ	

The Receiving device shall also provide supply voltage and signal return outputs to power the Transmitting device. These outputs shall meet the requirements in Table 6.3.2-2 over the entire Receiving device environmental requirement range.

TABLE 6.3.2-2 – RECEIVER POWER SUPPLY REQUIREMENTS

Parameter			Limits (including component tolerances) Min	Max	Units	Test Conditions / Definitions
a.	V_{SUPPLY}	=	4.85	5.15	V	Supply Voltage
b.	I_{OUT}	=	20		mA	Available current for Transmitting device
c.	C_{LOAD}	=		10	µF	Supply to return load capacitance in transmitter
d.	$V_{GND-OFFSET}$	=		0.02	V	Signal return ground offset in Receiving device
e.	$V_{3.3SUPPLY}$	=	3.234	3.366	V	Internal 3.3 V supply (if needed by Receiver)

6.3.2.1 ESD Transient Suppressor

If necessary, a circuit element such as a transorb (back-to-back zener) or a varistor device may be added in one or more places to provide ESD protection. However, when these devices are used they may add capacitance or introduce voltage and/or temperature variability to the signal time constant. When such devices are used the device load capacitor shall be reduced by an amount equivalent to the capacitance of the ESD transient suppressor.

6.3.3 Bus Wiring Harness and ECU Connectors

Combined resistance for all connector shall have less than 1 Ohms per line over total vehicle life. The bus wiring shall utilize cables with less than 0.1 nF per meter of wire length. The maximum cable length shall be 5 meters.

6.4 ESD Immunity

The transmitting and receiving module I/O pins shall withstand electrostatic discharges without any damage to the transmitting or receiving module when subjected to testing per the vehicle manufacturer's component Electrostatic Discharge test. The particular vehicle manufacturer's component technical specification shall state the Criticality Level of the device.

6.5 EMC Testing Requirements

The physical layer, when incorporated into an ECU or sensor design, shall function as specified in the device's intended electromagnetic environment. Additionally, the electromagnetic emissions produced during signal related operations shall not interfere with the normal operation of other ECU's or subsystems.

The particular vehicle manufacturer's component technical specification shall state the EMC testing requirements of the device.

6.6 Fault Protection Modes

Data communications may be interrupted under short of any impedance to supply or ground.

1. Wiring Short to Ground – There shall be no damage to any device when the signal or supply line is shorted to ground. An impedance of less than 50 ohms between the line and ground shall be considered a short to ground. Upon removal of the fault, a transmitter reset may occur and normal operation shall resume within the transmitter reset time. Operator intervention (for example a key cycle) shall not be required.
2. Wiring Short to Supply – There shall be no damage to any device when the signal or ground line is shorted to sensor supply V_{OUT}. An impedance of less than 50 ohms between the line and V_{OUT} shall be considered a short. Upon removal of the fault, a transmitter reset may occur and normal operation shall resume within the transmitter reset time. Operator intervention (for example a key cycle) shall not be required.

7. CONFIGURATION SHORTHAND

7.1 Shorthand Definition

A shorthand description for the various optional configurations is constructed using the following format and Table. Elements of the table are separated by dashes to form the final shorthand notation.

TABLE 7.1-1 – SENT CONFIGURATION SHORTHAND DEFINITION

Shorthand Description	Format	Requirements
SENT SAE J2716 revision	SENTxxxx	One of the following values depending on SENT revision supported: • 2007 • 2008 • 2010
Clock Tick Length [μs]	xx.xus	03.0 ≤ xx.x ≤ 90.0
Number of Data Nibbles	xdn	1 ≤ x ≤ 6
Pause Pulse Option	npp pp ppc(xxx.x)	no pause pulse pause pulse pause pulse with constant frame length, xx is number of clock ticks, 282.0 ≤ xxx.x ≤ 922.0 (for 6 data nibbles)
Use of Serial Protocol	ssp esp nsp	short serial protocol enhanced serial protocol no serial protocol
Sensor Type	ns A.1 A.3 A.4 D.1xxx …	Not specified here (see manufacturer specification) Dual Throttle Position sensors described in Appendix A.1 Single Secure sensors described in Appendix A.3 Single sensors described in Appendix A.4 Sensors class given in Table D.4-1, xxx are nibble values for bits D_{11} through D_0 (Appendix D represents the sensors defined in Appendices A.2 and A.5) Additional appendices may be defined and referenced

Example Shorthand Description:

SENT2010-03.0us-6dn-ppc(282.0)-nsp-A.1

- or single secure sensor application.

8. NOTES

8.1 Marginal Indicia

A change bar (l) located in the left margin is for the convenience of the user in locating areas where technical revisions, not editorial changes, have been made to the previous issue of this document. An (R) symbol to the left of the document title indicates a complete revision of the document, including technical revisions. Change bars and (R) are not used in original publications, nor in documents that contain editorial changes only.

PREPARED BY THE SAE SENT TASK FORCE
OF THE SAE VEHICLE ARCHITECTURE FOR DATA COMMUNICATIONS COMMITTEE

APPENDIX A RECOMMENDED APPLICATION SPECIFIC PROTOCOLS

This Appendix gives SENT protocol details for certain sensor applications. A nibble order summary is given in Table A-1.

TABLE A-1 - APPLICATION SPECIFIC SENT DATA CHANNEL NIBBLE ORDER

Appendix	**Data 1**	**Data 2**	**Data 3**	**Data 4**	**Data 5**	**Data 6**
A.1 Throttle Position	Ch1 MSN	Ch1 MidN	Ch1 LSN	Ch2 LSN	Ch2 MidN	Ch2 MSN
A.2 Mass Air Flow	Ch1 MSN	Ch1 MidMSN	Ch1 MidLSN	Ch1/Ch2 LSN	Ch2 LSN/ MidN	Ch2 MSN
A.3 Single Secure	Ch1 MSN	Ch1 MidN	Ch1 LSN	Counter MSN	Counter LSN	Inverted Copy Ch1 MSN
A.4 Single Sensors	Ch1 MSN	Ch1 MidN	Ch1 LSN	Counter MSN	Counter LSN	Zero or Inv Copy Ch1 MSN
A.5 Pressure or Pressure/Secure	Ch1 MSN	Ch1 MidN	Ch1 LSN	Ch2 LSN or Counter MSN	Ch2 MidN or Counter LSN	Ch2 MSN or Inv Copy Ch1 MSN

A.1 DUAL THROTTLE POSITION SENSORS

Specific additional requirements for the application of the protocol to dual sensor Electronic Throttle Control systems shall be as follows:

- Sensor 1 and sensor 2 are transmitted as equal and opposite slope sensor readings to balance the length of most signal transmissions (see Table A.1-1).
  - Data order:
    - data nibble 1: TPS1 MSN
    - data nibble 2: TPS1 MidN
    - data nibble 3: TPS1 LSN
    - data nibble 4: TPS2 LSN
    - data nibble 5: TPS2 MidN
    - data nibble 6: TPS2 MSN
  - Data vector (ordered MSB to LSB) is first divided into 4-bit groups corresponding to the nibbles. The nibble order of TPS 2 is then reversed.
- When an individual sensor is determined to be in error, the nibbles for that sensor will be all set to 0xF (TPS1) or 0x0 (TPS2) transmitting 100 % throttle position.
- When throttle 1 is determined to be in error, bit 0 of the Status Nibble is set to 1 otherwise bit set to 0.
- When throttle 2 is determined to be in error, bit 1 of the Status Nibble is set to 1 otherwise bit set to 0.
- Details serial message: Not required for throttle application.

TABLE A.1-1 - NIBBLE AND BIT ORDERS FOR SENT THROTTLE APPLICATIONS

Sensor Data	**Bit Weight**	**SENT Nibble Bits**	**SENT Nibble**
S&C [3] Serial Data Channel	-	S&C [3]	Status and Communication
S&C [2] Serial Data Channel	-	S&C [2]	
S&C [1] Channel 2 Indicator	-	S&C [1]	
S&C [0] Channel 1 Indicator	-	S&C [0]	
Channel 1 Data [11]	2^{11}	Channel 1 MSN [3]	Data 1 Channel 1 MSN
Channel 1 Data [10]	2^{10}	Channel 1 MSN [2]	
Channel 1 Data [9]	2^{9}	Channel 1 MSN [1]	
Channel 1 Data [8]	2^{8}	Channel 1 MSN [0]	
Channel 1 Data [7]	2^{7}	Channel 1 MidN [3]	Data 2
Channel 1 Data [6]	2^{6}	Channel 1 MidN [2]	

Channel 1 Data [5]	2^5	Channel 1 MidN [1]	Channel 1 MidN
Channel 1 Data [4]	2^4	Channel 1 MidN [0]	
Channel 1 Data [3]	2^3	Channel 1 LSN [3]	Data 3 Channel 1 LSN
Channel 1 Data [2]	2^2	Channel 1 LSN [2]	
Channel 1 Data [1]	2^1	Channel 1 LSN [1]	
Channel 1 Data [0]	2^0	Channel 1 LSN [0]	
Channel 2 Data [3]	2^3	Channel 2 LSN [3]	Data 4 Channel 2 LSN
Channel 2 Data [2]	2^2	Channel 2 LSN [2]	
Channel 2 Data [1]	2^1	Channel 2 LSN [1]	
Channel 2 Data [0]	2^0	Channel 2 LSN [0]	
Channel 2 Data [7]	2^7	Channel 2 MidN [3]	Data 5 Channel 2 MidN
Channel 2 Data [6]	2^6	Channel 2 MidN [2]	
Channel 2 Data [5]	2^5	Channel 2 MidN [1]	
Channel 2 Data [4]	2^4	Channel 2 MidN [0]	
Channel 2 Data [11]	2^{11}	Channel 2 MSN [3]	Data 6 Channel 2 MSN
Channel 2 Data [10]	2^{10}	Channel 2 MSN [2]	
Channel 2 Data [9]	2^9	Channel 2 MSN [1]	
Channel 2 Data [8]	2^8	Channel 2 MSN [0]	

A.2 MASS AIR FLOW SENSORS

This appendix describes the application of the SENT interface for Mass Air Flow (MAF) sensors. In addition to the MAF signal, MAF sensors optionally can deliver pressure data over the SENT fast channels

Air temperature at MAF, Humidity and Barometric pressure can be optionally transmitted over the slow channel.

A.2.1 Data Channels for MAF Sensors

TABLE A.2.1-1 - DATA CHANNELS FOR MAF SENSORS

Sensor Configuration	**Data Channels**		
	Fast Channel 1	**Fast Channel 2**	**Slow Channel**
MAF	MAF (16 bit)		
MAF / Pressure	MAF (16 bit)	Pressure (8 bit)	
MAF / Pressure/ Auxiliary measurements	MAF (16 bit)	Pressure (8 bit)	Temperature, and/or Humidity, and/or Barometric pressure
MAF / Pressure	MAF (14 bit)	Pressure (10 bit)	
MAF / Pressure/ Auxiliary measurements	MAF (14 bit)	Pressure (10 bit)	Temperature, and/or Humidity, and/or Barometric pressure

Table A.2.1-1 lists the various sensor configurations for MAF sensor applications. MAF sensors with high-resolution MAF signal and limited requirements on the pressure signal partition the six data nibbles (24 bit) into 16 bit for the MAF signal and 8 bit for the air pressure at the MAF. The air pressure at the MAF can be for example the Inlet Depression (Air pressure downstream of the air filter).

Specific additional requirements for the application of the protocol to Mass Air Flow (MAF) Measurement systems are as follows (see Table A.2.1-2 for nibble and bit order):

- First 4 nibbles are used to transmit 16 bit mass air flow measurement.
  - Data order:
    - data nibble 1: MAF MSN
    - data nibble 2: MAF MidMSN
    - data nibble 3: MAF MidLSN
    - data nibble 4: MAF LSN
  - Scaling
    - Application defined

- Next 2 nibbles used to transmit 8 bit pressure of the air flow at the MAF sensor.
  - Data order:
    - data nibble 5: Pressure at the MAF sensor LSN
    - data nibble 6: Pressure at the MAF sensor MSN
  - Data vector (ordered MSB to LSB) is first divided into 4-bit groups corresponding to the nibbles. The nibble order of Channel 2 (Pressure) is then reversed.
  - Scaling
    - Application defined
- When Reserved Signaling Code Ranges of Section A.2.4 are not used and the mass air flow is determined to be in error, the nibbles for that sensor will be all set to 0 (transmitting 0).
- When Signaling Code Ranges of Section A.2.4 are not used and the Pressure at the MAF sensor is determined to be in error, the nibbles for that sensor will be all set to 0 (transmitting 0 kPa).

TABLE A.2.1-2 - NIBBLE AND BIT ORDERS FOR SENT 16-BIT MAF, 8-BIT PRESSURE APPLICATIONS

Sensor Data	Bit Weight	SENT Nibble Bits	SENT Nibble
S&C [3] Serial Data Channel	-	S&C [3]	Status and Communication
S&C [2] Serial Data Channel	-	S&C [2]	
S&C [1] Channel 2 Indicator	-	S&C [1]	
S&C [0] Channel 1 Indicator	-	S&C [0]	
Channel 1 Data [15]	2^{15}	Channel 1 MSN [3]	Data 1
Channel 1 Data [14]	2^{14}	Channel 1 MSN [2]	
Channel 1 Data [13]	2^{13}	Channel 1 MSN [1]	Channel 1 MSN
Channel 1 Data [12]	2^{12}	Channel 1 MSN [0]	
Channel 1 Data [11]	2^{11}	Channel 1 MidMSN [3]	Data 2
Channel 1 Data [10]	2^{10}	Channel 1 MidMSN [2]	
Channel 1 Data [9]	2^{9}	Channel 1 MidMSN [1]	Channel 1 MidMSN
Channel 1 Data [8]	2^{8}	Channel 1 MidMSN [0]	
Channel 1 Data [7]	2^{7}	Channel 1 MidLSN [3]	Data 3
Channel 1 Data [6]	2^{6}	Channel 1 MidLSN [2]	
Channel 1 Data [5]	2^{5}	Channel 1 MidLSN [1]	Channel 1 MidLSN
Channel 1 Data [4]	2^{4}	Channel 1 MidLSN [0]	
Channel 1 Data [3]	2^{3}	Channel 1 LSN [3]	Data 4
Channel 1 Data [2]	2^{2}	Channel 1 LSN [2]	
Channel 1 Data [1]	2^{1}	Channel 1 LSN [1]	Channel 2 LSN
Channel 1 Data [0]	2^{0}	Channel 1 LSN [0]	
Channel 2 Data [3]	2^{3}	Channel 2 LSN [3]	Data 5
Channel 2 Data [2]	2^{2}	Channel 2 LSN [2]	
Channel 2 Data [1]	2^{1}	Channel 2 LSN [1]	Channel 2 LSN
Channel 2 Data [0]	2^{0}	Channel 2 LSN [0]	
Channel 2 Data [7]	2^{7}	Channel 2 MSN [3]	Data 6
Channel 2 Data [6]	2^{6}	Channel 2 MSN [2]	
Channel 2 Data [5]	2^{5}	Channel 2 MSN [1]	Channel 2 MSN
Channel 2 Data [4]	2^{4}	Channel 2 MSN [0]	

MAF sensors with specific requirements on the pressure signal partition the six data nibbles (24 bit) into 14 bit for the MAF signal and 10 bit for the air pressure at the MAF (see Table A.2.1-3 for nibble and bit order). Sensors using this format shall use the Enhanced Serial Message Format if serial messages are transmitted.

- First 4 nibbles are used to transmit 14 bit mass air flow measurement
  - Data order:
    - data nibble 1: MAF MSN
    - data nibble 2: MAF MidMSN
    - data nibble 3: MAF MidLSN
    - data nibble 4, LSN (nibble bit 3,bit 2: are MAF LSB s 1, 0)
  - Scaling
    - Application defined

- Next 2 nibbles used to transmit 10 bit pressure of the air flow at the MAF
  - Data order:
    - data nibble 4, bit 1,bit 0: Pressure at MAF LSB bit 1, bit 0 are Pressure at MAF LSBs 1, 0)
    - data nibble 5: Pressure at MAF MidN
    - data nibble 6: Pressure at MAF MSN
  - Data vector (ordered MSB to LSB) is first divided into 4-bit groups corresponding to the nibbles. The nibble order of Channel 2 (Pressure) is then reversed. Note, that data nibble 4 is the LSN of Channel 1 as well as Channel 2 and it carries the LSBs of the MAF and of the Pressure at MAF data.
  - Scaling

Application defined

TABLE A.2.1-3 - NIBBLE AND BIT ORDERS FOR SENT 14-BIT MAF, 10-BIT PRESSURE APPLICATIONS

Sensor Data	**Bit Weight**	**SENT Nibble Bits**	**SENT Nibble**
S&C [3] Serial Data Channel	-	S&C [3]	Status and Communication
S&C [2] Serial Data Channel	-	S&C [2]	
S&C [1] Channel 2 Indicator	-	S&C [1]	
S&C [0] Channel 1 Indicator	-	S&C [0]	
Channel 1 Data [13]	2^{13}	Channel 1 MSN [3]	Data 1
Channel 1 Data [12]	2^{12}	Channel 1 MSN [2]	
Channel 1 Data [11]	2^{11}	Channel 1 MSN [1]	Channel 1 MSN
Channel 1 Data [10]	2^{10}	Channel 1 MSN [0]	
Channel 1 Data [9]	2^9	Channel 1 MidMSN [3]	Data 2
Channel 1 Data [8]	2^8	Channel 1 MidMSN [2]	
Channel 1 Data [7]	2^7	Channel 1 MidMSN [1]	Channel 1 MidMSN
Channel 1 Data [6]	2^6	Channel 1 MidMSN [0]	
Channel 1 Data [5]	2^5	Channel 1 MidLSN [3]	Data 3
Channel 1 Data [4]	2^4	Channel 1 MidLSN [2]	
Channel 1 Data [3]	2^3	Channel 1 MidLSN [1]	Channel 1 MidLSN
Channel 1 Data [2]	2^2	Channel 1 MidLSN [0]	
Channel 1 Data [1]	2^1	Channel 1,2 LSN [3]	Data 4
Channel 1 Data [0]	2^0	Channel 1,2 LSN [2]	
Channel 2 Data [1]	2^1	Channel 1,2 LSN [1]	Channel 1,2 LSN
Channel 2 Data [0]	2^0	Channel 1,2 LSN [0]	
Channel 2 Data [5]	2^5	Channel 2 MidN [3]	Data 5
Channel 2 Data [4]	2^4	Channel 2 MidN [2]	
Channel 2 Data [3]	2^3	Channel 2 MidN [1]	Channel 2 MidN
Channel 2 Data [2]	2^2	Channel 2 MidN [0]	
Channel 2 Data [9]	2^9	Channel 2 MSN [3]	Data 6
Channel 2 Data [8]	2^8	Channel 2 MSN [2]	
Channel 2 Data [7]	2^7	Channel 2 MSN [1]	Channel 2 MSN
Channel 2 Data [6]	2^6	Channel 2 MSN [0]	

A.2.2 Status and Communication Nibble Error Flags

- When the mass air flow signal is determined to be in error, bit 0 of the Status Nibble is set to 1 otherwise bit set to 0.
- When the Pressure at the MAF sensor signal is determined to be in error, bit 1 of the Status Nibble is set to 1 otherwise bit set to 0.

A.2.3 Overview of Message IDs

- Table A.2-1 lists specific Message IDs when Short Serial Message Format is used
- Tables D.1-1 and D.2-1 lists specific Message IDs when Enhanced Serial Message Format is used
  - Individual slow channel sensor components (for example, air temperature, humidity or barometric pressure) are optional components and messages for these components do not need to be transmitted if the component is not present.
  - If message IDs according to D.1 are used, slow channel measurement data from sensor components shall be assigned as follows: Supplementary data channel #1 = temperature, supplementary data channel #2 = humidity, supplementary data channel #3 = barometric pressure.

- All scalings are application defined.
- If no temperature transfer characteristic is transmitted for supplementary data channel #1, the default temperature sensor transfer function characteristic from Section A.5.3.2 shall be used (12-bit numbers represent the temperature range from 200.125 K to 711 K, message # 1,1, ID 1 0).

TABLE A.2-1 - SHORT SERIAL MESSAGE FORMAT MESSAGE IDS FOR MASS AIR FLOW SENSOR SERIAL DATA

Message ID	Sensed Value **for Data Field**
0	Air Temperature (high byte)
1	Air Temperature (low byte)
2	Humidity (high byte)
3	Humidity (low byte)
4	Barometric Pressure(high byte)
5	Barometric Pressure(low byte)
6	Reserved
7	Reserved
8	Reserved
9	Reserved
A	Reserved
B	Reserved
C	Reserved
D	Reserved
E	Reserved
F	Error Codes

- Short Serial Message Format Serial message error codes bit encoding are listed in Table A.2-2.
  - If no errors are present, message F does not need to be transmitted.

TABLE A.2-2 - ERROR CODES FOR MESSAGE ID F, SHORT SERIAL MESSAGE FORMAT MASS AIR FLOW SENSOR SERIAL DATA

Error Code Bit Encoding	Bit (least significant to most significant)
Air Temperature Out-of-range High	0
Air Temperature Out-of-range Low	1
Humidity Out-of-range High	2
Humidity Out-of-range Low	3
Barometric Pressure Out-of-range High	4
Barometric Pressure Out-of-range Low	5
Reserved	6
Reserved	7

A.2.4 Reserved Signaling Code Ranges

The Reserved Signaling Code Ranges are required when the Enhanced Serial Message is implemented. They can be optionally used for sensors that do not implement the Enhanced Serial Message. In this case the full data ranges from 0 to 65535 and 0 to 255 shall be used. The receiver module must know a priori the scaling used.

Eight of the possible 16-bit, 14-bit, 10-bit or 8-bit values transmitted in each 'fast channel' are used for signalling purposes related to the measurement data of the particular channel.

- Address *0* Initialization
  - Address $(2^{Channel\_bitwidth}-7).....(2^{Channel\_bitwidth}-1)$ Error codes/ specific messages/ reserved codes

The particular width of the fast channel (16-bit, 14-bit, 10-bit or 8-bit) is denoted by *Channel_bitwidth*. Table A.2.4-1 explains the partitioning of the address space of fast channel 1 and 2. The particular addresses of the signalling codes are specified in Section A.2.5.

TABLE A.2.4-1 - MEASUREMENT DATA AND SIGNALING DATA REGIONS OF CHANNEL 1 AND CHANNEL 2 DATA

Data Channel Signal	**Data Class**	**16-bit Values**		**14-bit Values**		**10-bit Values**		**8-bit Values**	
		Address	Number of Values	Address	Number of Values	Ad-dress	Num-ber of Values	Ad-dress	Num-ber of Values
Error Codes / specific messages	Signaling	65529 … 65535	7	16377 … 16383	7	1017 … 1023	7	249 … 255	7
Channel 1 or Channel 2 Data	Measure-ment Data	1 … 65528	65528	1 …16376	16376	1 … 1016	1016	1 … 248	248
Initial-ization	Signaling	0	1	0	1	0	1	0	1

A.2.5 Data Nibble Reserved Values

Table A.2.5-1 specifies the assignment of the eight reserved addresses to the error codes, diagnostic messages and the initialization message.

TABLE A.2.5-1 - ERROR CODE / SPECIFIC CODE MESSAGES

Address	**Definition**	**Comment**
$2^{Channel\_bitwidth}-1$	Diagnostic mode	Used to indicate diagnostic state of sensor (e.g. for manufacturing purposes)
$2^{Channel\_bitwidth}-2$	Free to define by OEM/Supplier	
$2^{Channel\_bitwidth}-3$	Reserved	
$2^{Channel\_bitwidth}-4$	Reserved	
$2^{Channel\_bitwidth}-5$	Temporary error	Generic temporary error
$2^{Channel\_bitwidth}-6$	Diagnostic error (Optional: Diagnostic details in slow channel)	Diagnostic messages in slow channel as defined in Section D.5.
$2^{Channel\_bitwidth}-7$	Not a valid measurement value	Invalid data values, not-a-number
0	Initialization	The initialization message is transmitted during the sensor initialization phase until valid pressure/temperature values are available.

A.2.6 Encoding Mass Air Flow Transfer Functions

Linear transfer function characteristics of mass air flow sensors can be transmitted from the sensor to the ECU using Enhanced Serial Message Message IDs #07 through #0A (see Appendix D). These messages define the coordinates of the nodes nodes X_1, Y_1 and X_2 and Y_2.

The Transfer Characteristic Nodes (X_1,Y_1) and (X_2,Y_2) for mass air flow sensors shall be encoded as follows. The conversion of 16 or 14-bit SENT mass air flow data M_{val} into physical mass air flow values (in kg/h) shall be made with the following formula:

$$M\,[kg/h] = \underbrace{X_1}_{Offset\ X} + \underbrace{\frac{X_2 - X_1}{Y_2 - Y_1}}_{Slope} \cdot \left(M_{Val} - \underbrace{Y_1}_{Offset\ Y} \right)$$

The range of mass air flow values, covered by a sensor, shall be determined by the Physical Value mass-air-flow indices X_1 and X_2 that specify the beginning and the end of the range of mass air flow values with guaranteed tolerances (see Figure A.2.6-1 and Table A.2.6-1).

The mass air flow indices X_1, X_2 shall be encoded using a 12-bit data format. If used, the total 12-bit (10-bit mantissa + 2-bit exponent) shall be communicated from the transmitter (sensor) to the receiver (ECU) using the optional slow serial message channel.

The representation of the mass air flow indices (in [kg/h]) shall use the following formula

$$X_i = X_{m,i} \cdot 10^{Xe,i}$$

Mantissa $X_{m,i}$: 10-bit signed [-512 - 511]
Exponent $X_{e,i}$: 2-bit unsigned [0 – 3]

TABLE A.2.6-1 - 12-BIT REPRESENTATION OF THE TRANSFER CHARACTERISTIC NODE VALUES X_I (IN [KG/HOUR])

Data bit	D_{11}	D_{10}	D_9	D_8	D_7	D_6	D_5	D_4	D_3	D_2	D_1	D_0
Encoded mass air flow value X_i	$X_{m,i,9}$	$X_{m,i,8}$	$X_{m,i,7}$	$X_{m,i,6}$	$X_{m,i,5}$	$X_{m,i,4}$	$X_{m,i3}$	$X_{m,i,2}$	$X_{m,i,1}$	$X_{m,i,0}$	$X_{e,i,1}$	$X_{e,i,0}$

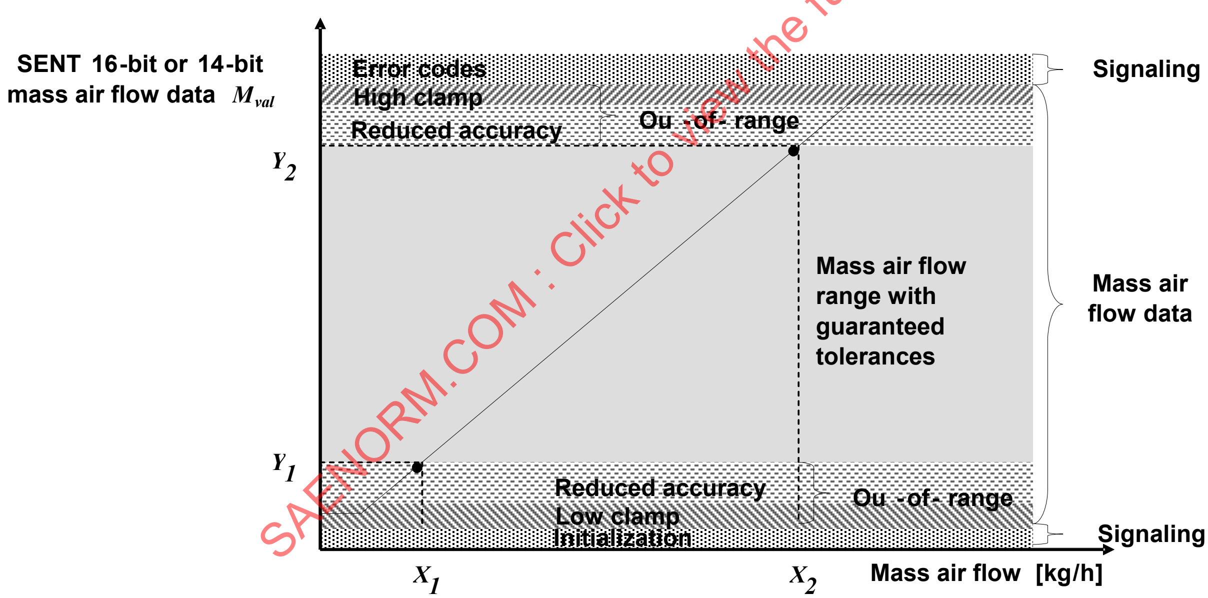


FIGURE A.2.6-1 - GUARANTEED MASS AIR FLOW RANGE, OUT-OF-RANGE VALUES AND SIGNALING DATA FOR MAF APPLICATIONS

Values Y_1 and Y_2 of the transfer characteristic nodes are transmitted using the enhanced serial message format with 12-bit data fields, if the LSBs of Y_1 and Y_2 are assumed to be zero. The SENT mass air flow data values transmitted over fast channel 1 use 16-bit or 14-bit data words. This means that data bits D_{11} to D_0 of the enhanced serial message carry $Y_{1,15}$ to $Y_{1,4}$ in case of 16-bit data words or $Y_{1,13}$ to $Y_{1,2}$ in case of 14-bit data words.

A.3 SINGLE SECURE SENSORS

Specific additional requirements for the application of the protocol to individual secure sensor systems shall be as follows:

- Sensor value is transmitted as a 12 bit value in data nibbles 1 – 3.
  - Data order:
    - data nibble 1: MSN
    - data nibble 2: MidN
    - data nibble 3: LSN
- Data nibbles 4 and 5 are an 8 bit rolling counter 0 to 255 with rollover back to 0.
  - Data order:
    - data nibble 4: MSN
    - data nibble 5: LSN
- Data nibble 6 Inverted copy of nibble 1 (15 – nibble 1 value).
- When the sensor is determined to be in error, bit 0 of the Status Nibble is set to 1 otherwise bit set to 0.
- Bit 1 of the Status Nibble: always zero.
- Details serial message: Not required for single secure sensor application.

An example of a single secure sensor is a pedal position sensor which is used to determine driver intent. Secure sensor require sufficient diagnostics to ensure the integrity of the data being transmitted. For example, the rolling count is used to detect a stuck message or stuck message processing.

A.4 SINGLE SENSORS

Specific additional requirements for the application of the protocol to individual sensor systems shall be as follows:

- Sensor value is transmitted as a 12 bit value in data nibbles 1 – 3.
  - Data order:
    - data nibble 1: MSN
    - data nibble 2: MidN
    - data nibble 3: LSN
- Data nibbles 4 and 5 can be either an 8 bit rolling counter 0 to 255 with rollover back to 0 optional or set nibbles to zero.
  - Data order:
    - data nibble 4: MSN
    - data nibble 5: LSN
- Data nibble 6 Inverted copy of nibble 1 (15 – nibble 1 value) optional. Otherwise set nibble to zero.
- When the sensor is determined to be in error, bit 0 of the Status Nibble is set to 1 otherwise bit set to 0.
- Bit 1 of the Status Nibble: always zero.
- Details serial message: Not required for single secure sensor application.

A.5 PRESSURE SENSORS AND COMBINED PRESSURE AND TEMPERATURE SENSORS

Specific additional requirements for the application of the protocol to Pressure (P) sensors and Combined Pressure (P) and Temperature (T) measurement systems are listed in this section. These systems are characterized as follows:

- 1 or 2 fast data channel(s): P or T, P + P, P+T
- Serial message channel (optional)
- 12-bit digital representation of pressure and temperature data can be interpreted by means of transfer characteristic functions
- Some 12-bit data values are reserved for initialization information and error codes
- The slow serial message channel can optionally be used to transmit sensor transfer characteristic function(s) parameters
- The optional slow serial message channel can be used to convey measurement data from additional sources. In this way a supplementary data channel can be implemented using the serial message channel.

Simple sensors which do not implement the serial channel use default sensor parameters. These sensor parameters have to be known by the receiver-side to be able to interpret the 12-bit measurement data values.

A.5.1 Data channels for pressure sensors and combined pressure and temperature sensors

Pressure sensors and combined pressure and temperature sensors shall make use of the following data channels provided by the SENT interface

- SENT signal 1 with data nibbles 1-3 carries a 12-bit data value. In the context of this appendix this denotes the “fast channel 1”
- SENT signal 2 with data nibbles 4-6 carries a 12-bit data value. In the context of this appendix this denotes the “fast channel 2”
- Bits 0 and 1 of the status and communication nibble serve as error indicators for fast channels 1 and 2.
- Sensors shall use the Enhanced Serial Message Format if serial messages are transmitted.

Specific combinations of sensors are listed in Table A.5.1-1.

TABLE A.5.1-1 - EXAMPLE CONFIGURATIONS OF PRESSURE SENSORS AND COMBINED PRESSURE AND TEMPERATURE SENSORS

Sensor Configuration		**Data Channels**		
		Fast channel 1 (Data nibbles 1-3)	**Fast channel 2** (Data nibbles 4-6)	**Slow channel** (status and communication nibble)
P	Pressure	Pressure	Not implemented (no data nibbles 4-6)	Sensor-specific parameters (transfer characteristic, sensor ID, type, manufacturer) Diagnostic,
P/-	Pressure	Pressure	Nibbles 4-6 are set to zero	Sensor-specific parameters (transfer characteristic, sensor ID, type, manufacturer) Diagnostic,
P/S	Pressure/Secure sensor	Pressure	Secure sensor information (see Appendix A.3)	Sensor-specific parameters (transfer characteristic, sensor ID, type, manufacturer) Diagnostic,
P/S/x	Pressure/Secure sensor/ Supplementary measurement data (e.g. temperature)	Pressure	Secure sensor information (see Appendix A.3)	Sensor-specific parameters and supplementary measurement (transfer characteristic, sensor ID, type, manufacturer) Diagnostic, Supplementary measurement data (e.g. temperature)
P1/P2	Pressure 1 / Pressure 2	Pressure 1	Pressure 2	Sensor-specific parameters (transfer characteristic, sensor ID, type, manufacturer) Diagnostic,
P/T	Pressure / Temperature	Pressure	Temperature	Sensor-specific parameters (transfer characteristic, sensor ID, type, manufacturer) Diagnostic
P/P/x	Pressure 1 / Pressure 2 / Supplementary measurement	Pressure 1	Pressure 2	Sensor-specific parameters and supplementary measurement (transfer characteristic, sensor ID,

Sensor Configuration		**Data Channels**		
		Fast channel 1 (Data nibbles 1-3)	**Fast channel 2** (Data nibbles 4-6)	**Slow channel** (status and communication nibble)
	data (e.g. temperature)			type, manufacturer) Diagnostic, Supplementary measurement data (e.g. temperature)

Figure A.5.1-1 - explains the allocation of the SENT data nibbles to the fast channel 1, fast channel 2 and the status and communication nibble that conveys the slow serial channel.

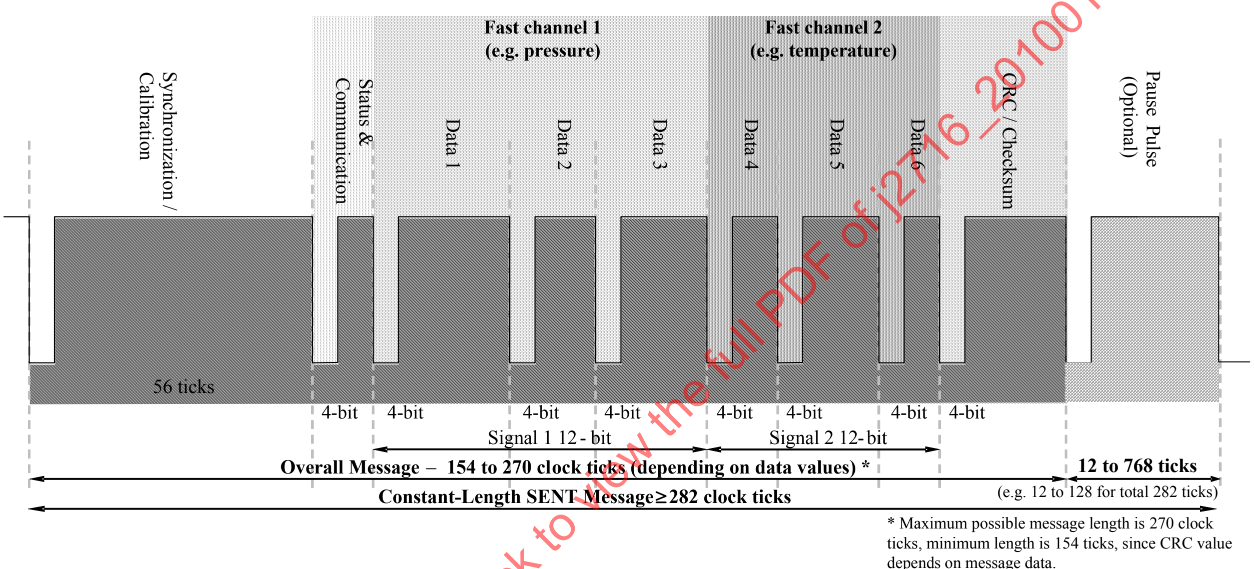


FIGURE A.5.1-1 - DATA CHANNELS FOR PRESSURE SENSORS AND COMBINED PRESSURE AND TEMPERATURE SENSORS

The data channels for Pressure sensors and Combined Pressure and Temperature Measurement systems are defined as follows:

- Fast Channel 1
  - Data order:
    - data nibble 1: Channel 1 measurement data MSN
    - data nibble 2: Channel 1 measurement data MidN
    - data nibble 3: Channel 1 measurement data LSN
  - Scaling
    - Optionally determined by slow channel message IDs $07 through $0A (see section D.1). If the optional serial data channel is not implemented, application-specific transfer characteristics have to be known by the receiver
  - Error Flags
    - When the fast channel 1 measurement data is determined to be in error, bit 0 of the Status Nibble shall be set to 1 otherwise bit 0 shall be set to 0 (see Table A.5.1-2)
- Fast Channel 2
  - Data order:
    - data nibble 4: Channel 2 measurement data LSN or secure sensor counter MSN
    - data nibble 5: Channel 2 measurement data MidN or secure sensor counter LSN
    - data nibble 6: Channel 2 measurement data MSN or secure sensor inverted copy of nibble 1
  - Data vector (ordered MSB to LSB) is first divided into 4-bit groups corresponding to the nibbles. The nibble order of Channel 2 is then reversed.

- Scaling
  - Optionally determined by slow channel message IDs $0B through $0E (see section D.1). If the optional serial data channel is not implemented, application-specific transfer characteristics have to be known by the receiver
- Error Flags
  - When the fast channel 2 measurement data is determined to be in error, bit 1 of the Status Nibble shall be set to 1 otherwise bit 1 shall be set to 0 (see Table A.5.1-2)
  - If fast channel 2 is not implemented, application code in the receiver is responsible to ignore the error flag in this case
- When channel 2 is not implemented, the SENT message shall contain only 3 data nibbles or data nibbles 4-6 shall be all set to 0
- When a pressure sensor is used as a single secure sensor, data nibbles 1-6 shall be used as described in Appendix A.3. The serial message channel of the status and communication nibble may be optionally used.

TABLE A.5.1-2 - ALLOCATION OF THE BITS OF THE STATUS AND COMMUNICATION NIBBLE

Bit Number	Bit Function	Comment
0 (least significant)	Channel 1 Indicator (1 = error, 0 otherwise)	Error Flags
1	Channel 2 Indicator (1 = error, 0 otherwise)	
2	Serial Data message bits	Serial Data Channel
3 (most significant)	Serial Data message bits	

The serial message channel can be optionally used by pressure sensors and combined pressure and temperature sensors. This data channel can be used to transmit, albeit at a slower rate, additional information such as diagnostics information, encoding reference information and it can be used as a supplementary data channel.

A.5.2 Reserved Signaling Code Ranges

Eight of the 4096 possible 12-bit values transmitted in each 'fast channel' are used for signalling purposes related to the measurement data of the particular channel.

- Address 0 Initialization
- Address 4089 – 4095 Error codes/ specific messages/ reserved codes

Table A.5.2-1 explains the partitioning of the address space of fast channel 1 and 2. The particular addresses of the signaling codes are specified in Section A.5.7.

TABLE A.5.2-1 - MEASUREMENT DATA AND SIGNALING DATA REGIONS OF CHANNEL 1 AND CHANNEL 2 DATA

Data Channel Signal	**Data Class**	**12-bit Values**	
		Address	Number of Values
Error Codes / specific messages	Signaling	4089 … 4095	7
Channel 1 or Channel 2 Data	Measure-ment Data (11.997 bit resolution)	1 … 4088	4088
Initialization	Signaling	0	1

The data region can be divided further into more regions, for example to describe a range with values with a guaranteed tolerance (See pressure sensor application in Section A.5.3.1.3).

A.5.3 Encoding Sensor Characteristic Transfer Functions

Linear transfer function characteristics of pressure sensors can be transmitted from the sensor to the ECU using slow channel Message IDs $07 through $0E (see Appendix D). These messages define the coordinates of the nodes X_1, Y_1 and X_2 and Y_2 defined (see Figure A.5.3-1). Such a function allows the coding of a range of measurement data values into 12-bit code values.

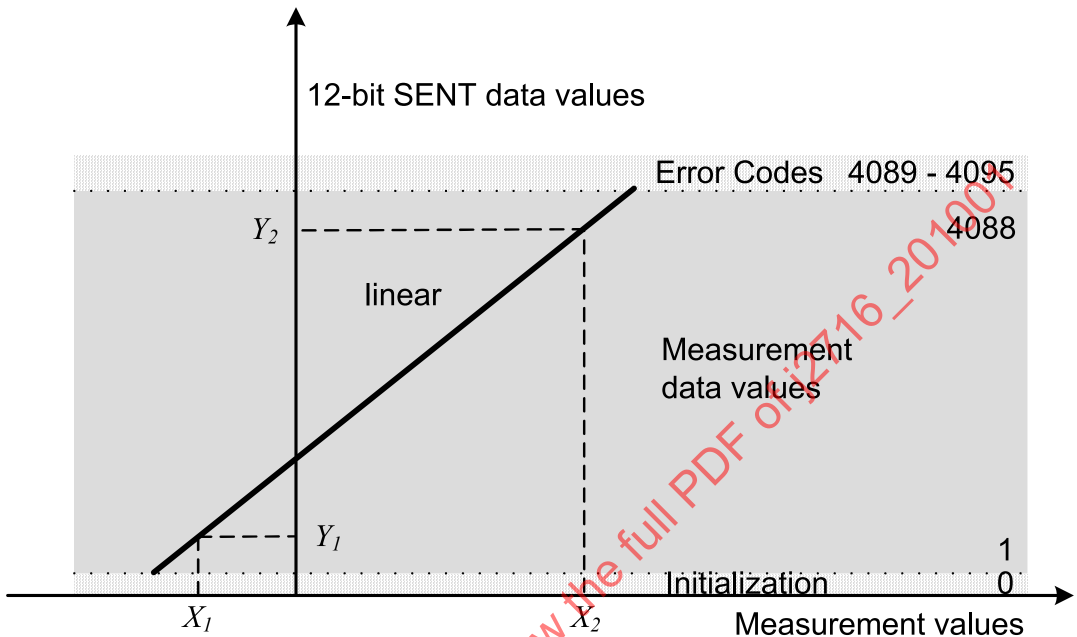


FIGURE A.5.3-1 - NOMINAL CHARACTERISTIC FUNCTION OF A SENSOR

Details for the transfer characteristic functions for encoding pressure and temperature are described in the sections below.

A.5.3.1 Pressure Sensor Transfer Functions

This section describes the mapping of pressure data to 12-bit values (numbers). The mapping includes guaranteed pressure range, out-of-range values and signaling data. The partition of the address space is defined either with default values Y_1, Y_2 or with sensor-specific values Y_1, Y_2 that are transmitted over the optional slow serial channel. The default values Y_1=193, Y_2=3896 indicate the beginning and the end of the default pressure range with guaranteed tolerances.

A.5.3.1.1 Encoding of Pressure Sensor Transfer Functions

The Transfer Characteristic Nodes (X_1,Y_1) and (X_2,Y_2) for pressure sensors shall be encodes as follow. The conversion of 12-bit SENT pressure data P_{val} into physical pressure values (in Pascal) shall be made with the following formula (see Figure A.5.3.1.1-1):

$$P[Pa] = \underbrace{X_1}_{Offset\ X} + \underbrace{\frac{X_2 - X_1}{Y_2 - Y_1}}_{Slope} \cdot \left(P_{Val} - \underbrace{Y_1}_{Offset\ Y} \right)$$

$$P[Pa] = \underbrace{X_1}_{Offset\ X} + \underbrace{\frac{X_2 - X_1}{Y_2 - Y_1}}_{Slope} \cdot \left(P_{Val} - \underbrace{Y_1}_{Offset\ Y} \right)$$

Physical pressure value — 12-bit digital representation

P_{Val}: 12-bit unsigned fixed-point integer number (0 .. 4095) Fast channel 1,2

X_1, X_2: Floating-point number (X_i calculated from $X_i = X_{m,i} \cdot 10^{Xe,i}$ [Pa])

Y_1, Y_2: Optional: Standardized default values *or* 12-bit unsigned fixed-point integer number (1 .. 4088)*

* Address space for pressure data values

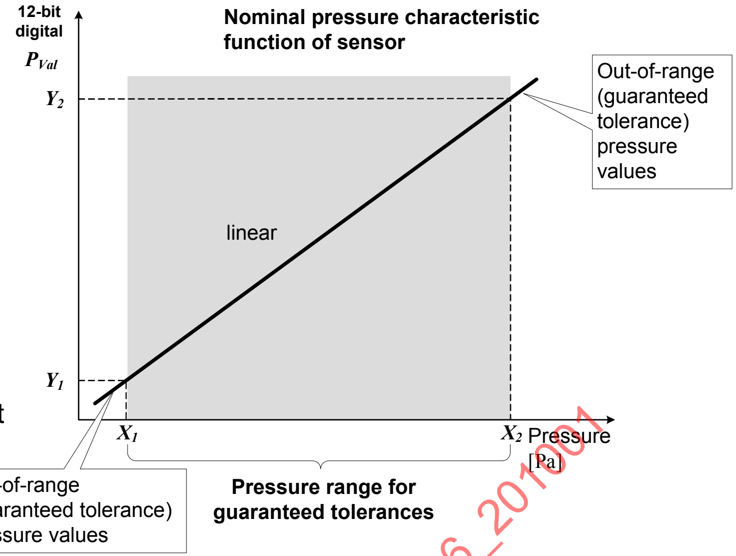


FIGURE A.5.3.1.1-1 - PRESSURE TRANSFER CHARACTERISTIC CURVE

A.5.3.1.2 Physical Value Pressure Indices

Since there are such a large variety of pressure sensors, the SENT interface has to cover the transmission of numerous different ranges of pressure values. The range of pressure values, covered by a sensor, shall be determined by the Physical Value Pressure Indices X_1 and X_2 that specify the beginning and the end of the range of pressure values with guaranteed tolerances.

The pressure indices X_1, X_2 shall be encoded using a 12-bit data format. If used, the total 12-bit (9-bit mantissa + 3-bit exponent) shall be communicated from the transmitter (sensor) to the receiver (ECU) using the optional slow serial message channel.

The representation of the pressure indices (in Pascal [Pa]) shall use the following formula

$$X_i = X_{m,i} \cdot 10^{Xe,i}$$

Mantissa $X_{m,i}$: 9-bit signed [-256 - 255]
Exponent $X_{e,i}$: 3-bit unsigned [0 – 7]

Specific interpretations of the mantissa and exponent shall be as given in Table A.5.3.1.2-1

TABLE A.5.3.1.2-1 - LIMITS OF PRESSURE RANGE: POSSIBLE VALUES FOR X_1, X_2

Pressure Range	**Step-width of limiting pressure values X_1 and X_2**	**Exponent X_{ei}**
-2.560e+002 …. 2.550e+002 [Pa] -2.560e-003 …. 2.550e-003 [bar]	1.0e+000 [Pa] 1.0e-005 [bar]	0
-2.560e+003 …. 2.550e+003 [Pa] -2.560e-002 …. 2.550e-002 [bar]	1.0e+001 [Pa] 1.0e-004 [bar]	1
-2.560e+004 …. 2.550e+004 [Pa] -2.560e-001 …. 2.550e-001 [bar]	1.0e+002 [Pa] 1.0e-003 [bar]	2
-2.560e+005 …. 2.550e+005 [Pa] -2.560e+000 …. 2.550e+000 [bar]	1.0e+003 [Pa] 1.0e-002 [bar]	3
-2.560e+006 …. 2.550e+006 [Pa] -2.560e+001 …. 2.550e+001 [bar]	1.0e+004 [Pa] 1.0e-001 [bar]	4
-2.560e+007 …. 2.550e+007 [Pa] -2.560e+002 …. 2.550e+002 [bar]	1.0e+005 [Pa] 1.0e+000 [bar]	5
-2.560e+008 …. 2.550e+008 [Pa] -2.560e+003 …. 2.550e+003 [bar]	1.0e+006 [Pa] 1.0e+001 [bar]	6
-2.560e+009 …. 2.550e+009 [Pa] -2.560e+004 …. 2.550e+004 [bar]	1.0e+007 [Pa] 1.0e+002 [bar]	7

The 12-bit data X_i shall be composed in the following way:
$X_i = [X_{m,i,8} \ldots X_{m,i,0}, X_{e,i,2} \ldots X_{e,i,0}]$ (see Table A.5.3.1.2-2 for the data bit encoding).

TABLE A.5.3.1.2-2 - 12-BIT REPRESENTATION OF THE TRANSFER CHARACTERISTIC NODE VALUES X_I (IN PASCAL [PA])

Data bit	D_{11}	D_{10}	D_9	D_8	D_7	D_6	D_5	D_4	D_3	D_2	D_1	D_0
Encoded pressure value X_i	$X_{m,i,8}$	$X_{m,i,7}$	$X_{m,i,6}$	$X_{m,i,5}$	$X_{m,i,4}$	$X_{m,i3}$	$X_{m,i,2}$	$X_{m,i,1}$	$X_{m,i,0}$	$X_{e,i,2}$	$X_{e,i,1}$	$X_{e,i,0}$
$X_i = X_{m,i} \cdot 10^{Xe,i}$	Mantissa									Exponent		

A.5.3.1.3 SENT 12-bit Pressure Indices

The SENT 12-bit Pressure Indices Y_1 and Y_2 are used to map the Physical value Pressure Indices to 12-bit SENT values. The SENT 12-bit Pressure Indices can take two optional forms:

- Default values, or
- sensor-specific values transmitted over the slow serial message channel

If the values Y_1 and Y_2 are not transmitted over the serial channel, the default partitioning of the data space, as specified in Figure A.5.3.1.3-1 and Table A.5.3.1.3-1 shall be applied (Y_1=193, Y_2=3896). This table also specifies the default guaranteed pressure range, out-of-range values and signaling data.

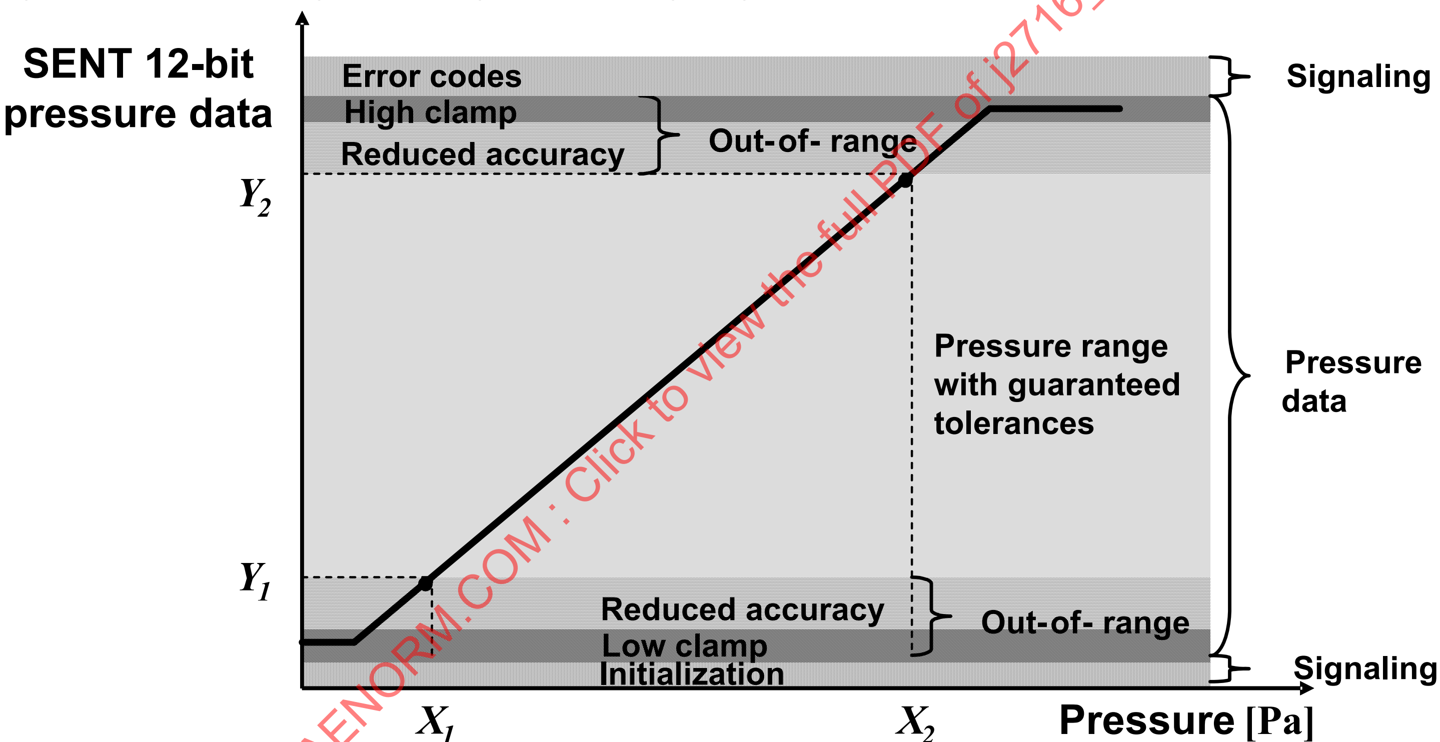


FIGURE A.5.3.1.3-1 - GUARANTEED PRESSURE RANGE, OUT-OF-RANGE VALUES AND SIGNALING DATA

TABLE A.5.3.1.3-1 - PARTITIONING OF THE PRESSURE DATA SPACE WITH DEFAULT Y1 AND Y2 : (Y1=193, Y2=3896)

Data Channel Signal	**Data Class**	**12-bit Values**	
		Address	Number of Values
Error Codes	Signaling	4089 … 4095	7
High Clamp	Pressure Data (11.997 bit resolution)	4088	1
Reduced Accuracy		3897 … 4087	191
Pressure with Guaranteed Tolerances		193 … 3896	3704
Reduced Accuracy		2 … 192	191
Low Clamp		1	1
Initialization	Signaling	0	1

If the SENT 12-bit Pressure Indices Y_1 and Y_2 are transmitted using the slow serial message channel, then Y_1, Y_2 shall be within pressure data range of 12-bit data which is defined by Low Clamp (=1) < Pressure Range < High Clamp (=4088). Values for Y_1, Y_2 outside the valid range result in an undefined condition.

A.5.3.2 Temperature Sensor Transfer Function Characteristics

The range of possible temperature values is small compared with the variety of pressure ranges. Therefore the standard defines one default characteristic function, that can be applicable to most sensors.
The default temperature transfer characteristic function shall be defined as:
Temperatures in Kelvin [K] with offset -200 K
Default Range: 200.125 K to 711 K

The temperature values T_{Val} that are transmitted as 12-bit SENT data shall be calculated with the formula

$$T_{Val} = (T[K] - 200\ K)/[K]$$

T_{Val} are12-bit unsigned fixed-point numbers with binary point between bit 2 and bit 3 (data range 0.125 to 511; 200.125 K to 711 K), see Figure A.5.3.2-1.

In addition there exists also an option to specify sensor specific temperature characteristics specified by sensor type in combination with a configuration code.
Examples of such sensor specific temperature characteristic are:
-Sensor types with nonlinear temperature scale(non-Kelvin, e.g. un-linearized NTC output). The particular non-linear temperature characteristic can be indicated by Message 04 (Configuration Code).
-Sensor types with non-default linear characteristics, for example, wider temperature range and coarser resolution. A linear Temperature Characteristic that differs from the default characteristic can be transmitted using fast Channel 2 Characteristic Nodes X_1, Y_1 and X_2 and Y_2 using Messages 0B, 0C, 0D, 0E.

If temperature is transmitted as fast-channel data, it shall always be transmitted in fast channel 2 when combined with pressure data. If temperature is transmitted over the serial message channel (slow channel), supplementary data message #1,1 (with ID# 1 0) shall carry the 12-bit temperature values.

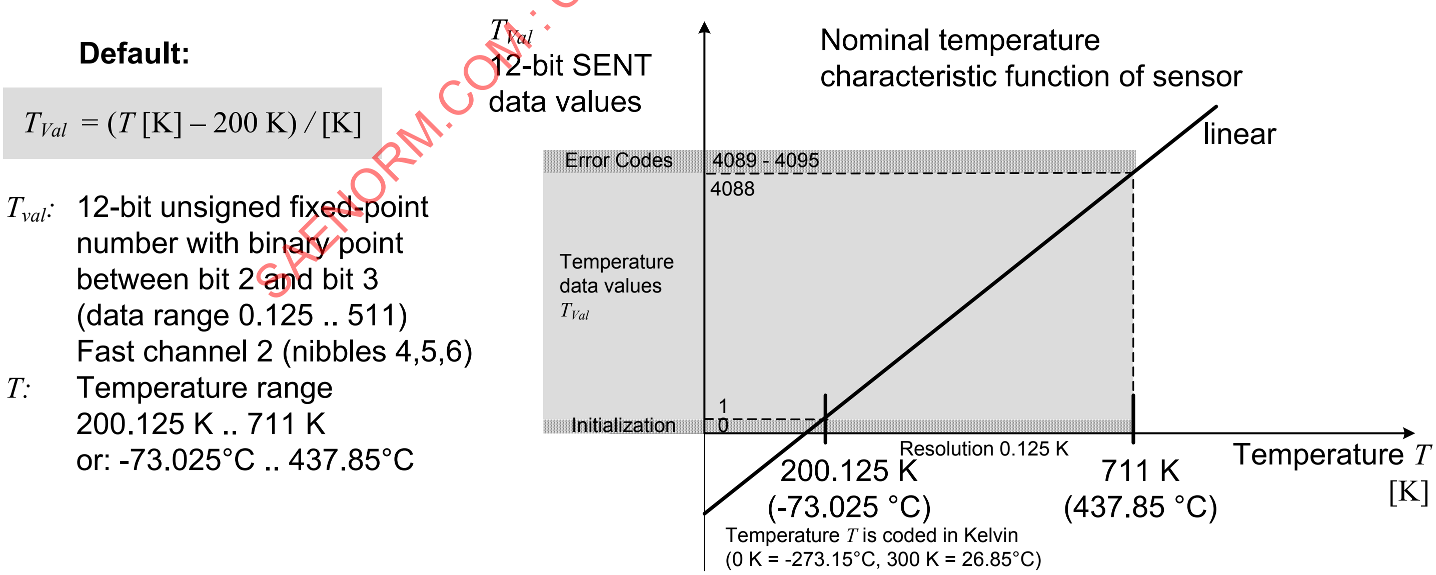


FIGURE A.5.3.2-1 - DEFAULT TEMPERATURE CHARACTERISTIC FUNCTION

A.5.4 Slow Channel Definition

The slow channel for sensors defined in Section A.5 shall be as defined in Appendix D.

A.5.5 Pressure Application Examples

Examples of encoding for pressure sensors and temperature sensors are illustrated in the next sections.

A.5.5.1 High Pressure Common Rail Sensor

Sensor Type = 8 bit code defined in catalog and transmitted over slow serial channel
X_1, X_2 transmitted in slow channel:
$X_{m,1}$=0, $X_{e,1}$=0
$X_{m,2}$=28, $X_{e,2}$=7
Defaults for Y_1, Y_2 (these are not transmitted): Y_1=193, Y_2=3896
Figure A.5.5.1-1 shows the scaling and diagnostic regions for these sensors.

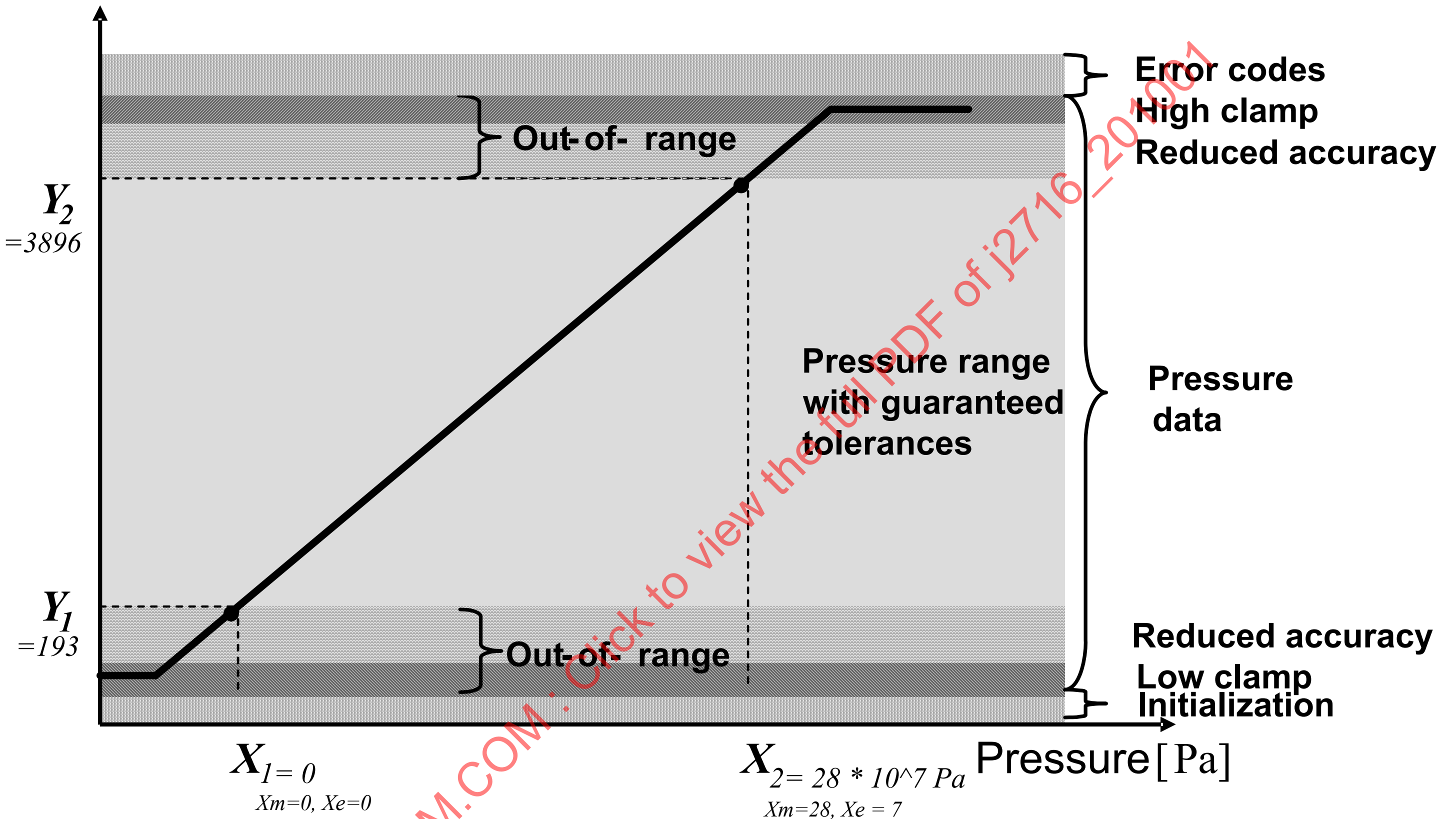


FIGURE A.5.5.1-1 - APPLICATION WITH DEFAULT Y_1, Y_2

A.5.5.2 Differential Pressure Sensor

Tank pressure sensor -2.5 kPa … 2.5 kPa
Transfer characteristic specified by X_1, X_2, Y_1 and Y_2
Node-values X_1, Y_1 and X_1, Y_2 can be transmitted over the slow serial channel. Figure A.5.5.2-1 shows the scaling and diagnostic regions for these sensors.

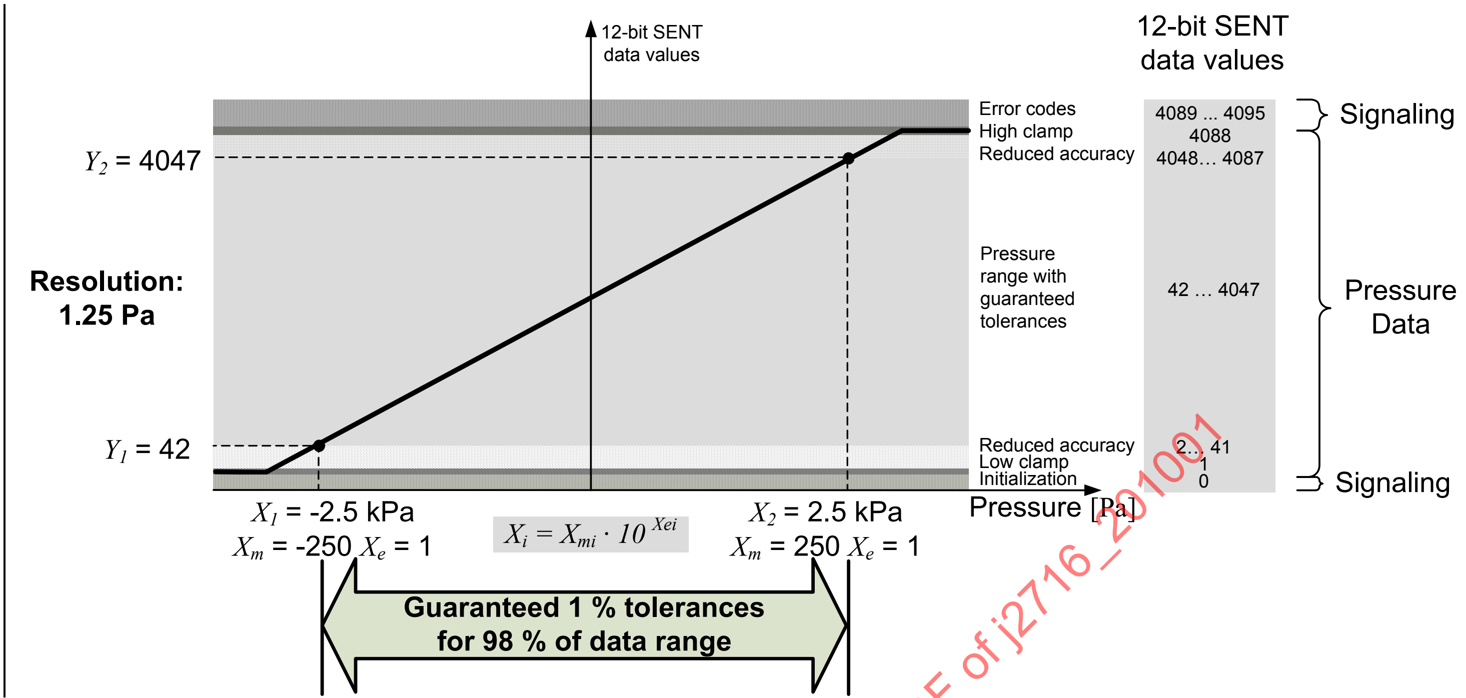


FIGURE A.5.5.2-1 - APPLICATION WITH SENSOR-SPECIFIC Y_1, Y_2

A.5.6 SENT Status and Error Messages

Pressure and combined pressure and temperature sensors can transmit error indication, error diagnostic and status information to the ECU-side. The occurrence of an error shall be indicated by the error flags for fast channel 1 and fast channel 2 (bit 0 and bit 1 of the status and communication nibble), as specified in Section A.5.1.

In addition to the Status and Communication nibble error flags, fast-channel error codes can also be transmitted instead of pressure or temperature measurement data using the reserved 12-bit addresses (see Section A.5.2). Transmission of diagnostic messages over the optional slow serial channel can be made in parallel to the transmission of pressure and temperature data over the fast data channels.

A.5.6.1 Receiver Error Flag Handling Recommendation

The Communication and Status nibble is not protected by the CRC of the SENT data frames. It is recommended that the receiver contain a mechanism, that takes into account the reduced reliability of single error flags (e.g. some filterin gor debouncing of the error flag).

A.5.6.2 Example Usage of Error Messages

Error scenarios:

Measurement data is available with restricted accuracy

- Error indication:
  - Error flag raised
- Error diagnosis:
  - Diagnostic messages over slow channel (if slow channel is implemented)

Example: Unreliable pressure data due to overheating of sensor