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Understanding Injection Current on NXP Automotive Microcontrollers

1 Introduction

NXP Semiconductors produces many microcontrollers (MCUs) specifically for the automotive market.

Automotive MCUs are designed with the following characteristics:

- Wafer process technology from 350 nanometers (nm) down to 90 nm[1]
- Target many different end uses, such as powertrain engine controllers, body controllers, chassis controllers, safety controllers, and cluster/infotainment
- Overall MCU performance—8-bit, 16-bit, and 32-bit
- Wide range of price targets, from low cost minimal feature set to higher cost, high performance MCUs

All of these factors have an impact on the allowable injection currents that a device can withstand without causing any long-term effect on the device lifetime. In general, injection current that induces a voltage on the internal structures higher than the operating voltage of the device can degrade the lifetime of the transistors and other internal circuitry. However, all of these conditions are taken into account and are covered by the design of each MCU to ensure proper device lifetime.

1. 55 nm devices are currently in development and qualification. A 55 nm device example will be added to in a future version of this document.

Contents

Factors that affect the injection current capabilities of an MCU are as follows:

- Wafer process technology (transistor geometry, support for high voltage transistors)
- MCU maximum junction temperature, which implies a maximum operating temperature
- Intended market space, which may imply a more aggressive lifetime temperature profile[2]

The following table shows the minimum transistor sizes for the different wafer process technologies and the device families in those wafer technologies. Minimum gate sized transistors are not generally used in the input and output (I/O) circuits of the device. Typically, the I/O circuits use larger transistors and even a thicker gate oxide to enhance the lifetime of the MCU input and output circuitry. For example, in both the 90 nm and the 55 nm processes, the transistors used in the I/O circuit have the same transistor gate width (0.72 micron [720 nm]) and have the same gate oxide thickness (150Å).

The following table shows the range of MCUs that are designed primarily for the automotive market.

Table 1. Example devices and wafer process technology size

Wafer process technology (minimum transistor gate size)	Example devices
350 nm	MPC555
250 nm	MPC56x, S08D, S08S, S12, S12X, S12Z
180 nm	S08RN, S12, S12X, S12Z
130 nm	MPC5534, MPC555x, MPC556x
90 nm	MPC560xB, MPC560xC, MPC560xD, MPC560xP, MPC560xS, MPC563xM, MPC564xB, MPC564xA, MPC564xS, MPC567xF, MPC5676R
55 nm	MPC5744P, MPC5744K, MPC5746M, MPC5777M

In addition to the transistor geometry and type, the maximum junction temperature for which a device is designed has an impact on the allowable injection current. Most automotive MCUs are designed for a maximum junction temperature (T_J) of 150°C; however, some families of devices may be designed for higher (165°C) or lower (125°C, or even lower) junction temperatures. The following table shows the typical junction temperatures for different types of automotive applications.

Table 2. Market space versus temperature ranges

Market space	Typical automotive location	Typical maximum junction temperature required
Infotainment	In passenger compartment	100°C
Body	Outside the passenger compartment	115°C
Safety	Outside or inside the passenger compartment and outside the engine compartment	115°C
Chassis	Outside the passenger compartment, but could be in the engine compartment, although not mounted directly on the engine itself	125°C
Powertrain	Inside the engine compartment or in the transmission	150°C or even 165°C

2. Under-hood Powertrain applications generally require a higher temperature profile over the life of the MCU than a MCU intended for the passenger compartment (such as the chassis controller or infotainment modules).

Generally, automotive systems have voltages that are typically higher than the operating voltages of the MCU. As CMOS transistor geometries get smaller and smaller, safe operating voltages on the internal transistors get lower. Therefore, inputs and outputs of the devices must use larger geometry transistors in the I/O circuits to protect the device from excessive voltages to prevent damage to the internal logic of the device. Each MCU data sheet specifies a number of different specifications that are allowed for a particular device in terms of maximum voltages on both the power supply pins[3] and to the input and output pins, as well as on the maximum currents that can be injected on a pin. Generally, on NXP's MCUs, protection circuits are included to allow for some injection current on all pins of the device; however, there are a small number of exceptions that are noted in the device data sheet. These I/O protection circuits are sized for particular applications based on requirements and cost targets of the MCU.

In should be noted that whenever current is injected into a pin of a device, that current must be dissipated. When the power supplies of the device are on, this generally is not an issue, unless the total injected current is higher than the current requirements of the device, in which case, the power supply itself must be capable of handling this current. In the other case, when the power supplies are off, injection current may cause the power supply to rise above 0 volts. In this case, it is important to ensure that the voltage is not too large and that the MCU is kept in reset when the voltage is lower than the minimum operating voltage of the device.

CAUTION

> When the MCU is in an unpowered state, current injected through the device pins may bias internal device structures (e.g. ESD diodes) and incorrectly power up these internal structures through inadvertent paths. The presence of such residual voltage may influence different device-internal blocks in an unpredictable manner and may ultimately result in unpredictable device behavior.
>
> Once in the illegal state, powering up the device further and then applying reset does not necessarily clear the illegal state.
>
> Injection current specified for the device under the aspect of absolute maximum ratings represent the capability of the internal circuitry to withstand such condition without causing physical damage. Functional operation of the device under conditions - specified as absolute maximum ratings - is not implied.

This application note describes injection currents in terms of the data sheet electrical specifications for normal recommended operating conditions and for error conditions that allow short-term violations of the recommended operating conditions as listed in the device absolute maximum injection current specifications. This application note also describes what should be done to protect the MCU from any damage due to over-voltage conditions on the I/O pins.

2 Typical Internal Input/Output Circuits

All pins implement protection diodes that protect against electrostatic discharge (ESD). In addition to providing protection from ESD, these diode circuits will also clamp the voltage to a diode drop above the supply of that pin segment[4]. In many cases, both digital and analog pins need to be connected to voltages that are higher than the operating voltage of the device pin. This is permissible as long as the injection current is limited as defined in the device specification. Current can be limited by adding a series resistor on the signal. The input protection diodes will keep the voltage at the pin at a safe level (according to the absolute maximum ratings of the device) as long as injection current is less than the maximum injection current specification.

NOTE

> In parts of this document, the terms VDDEx and VDDEHx are used for the generic supply voltages that power external pins of the device, regardless of the names used in the data sheets of individual devices. VDDEx represents a low voltage supply (usually

3. The generic term *pin* is used regardless of whether the device is in a leaded package or a ball grid array package.
4. Many devices have separate power supply "segments" for a set of I/O pins. In some devices, this allows certain peripherals to be powered at different voltages. For example, one peripheral could have 3.3 V I/O, while another peripheral has 5 V I/O. See the device data sheet to determine if different I/O pin sets (segments) have separate power supplies.

3.3 V or lower) and VDDEHx represents a high voltage supply (typically 5 V, though it could also be 3.3 V).

The figure below shows a typical I/O circuit for a pin.

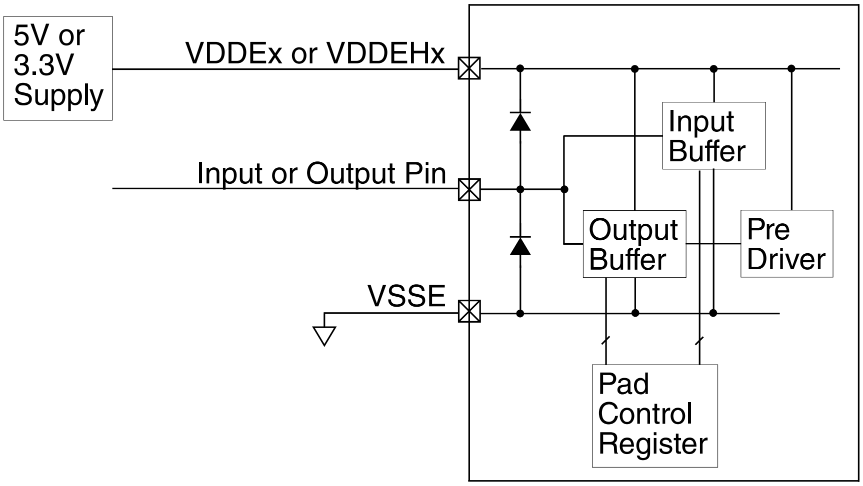

Figure 1. Typical I/O circuit

Additional circuits on the pins can be enabled only by fast ESD transients (these other circuits are not shown). In normal operation, these circuits have no effect on the pin characteristics and are only triggered by very fast, high voltage transients. To prevent turning on these circuits during normal power-up sequences, the ramp rate of the power supplies (all external supplies, 5 V, and if the internal regulators are not used, 3.3 V and 1.2 V) should not exceed 25 V/ms for most devices (some device power supplies are specified as 50 V/ms; see the data sheet of the device).

NOTE

See the actual data sheet for any overriding specifications, particularly for the maximum power supply ramp speed. Different devices may have different specifications. 25 V/ms is the MPC5674F and MPC5676R specification and may be more limiting than other devices that are specified as 50 V/ms. Most devices fall into one of these two specifications. The ramp rate needs to be limited to avoid enabling the additional ESD protection circuits on the device.

Some device families (130 nm [MPC5500 family] and some 250 nm devices) use a floating ESD rail. All power supplies and I/O pins are connected to this floating rail. The floating rail will float to 1 diode drop voltage above the highest voltage on the device. This is shown in the following figure.

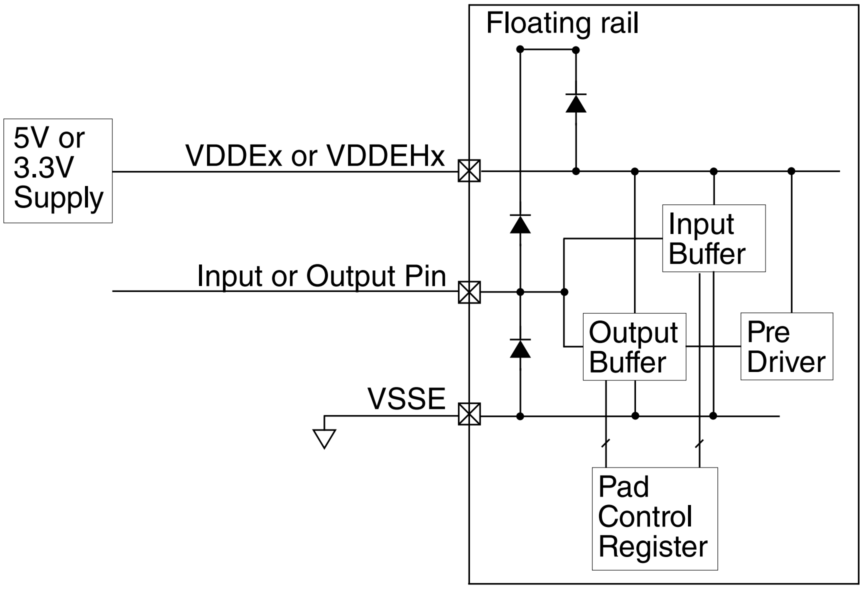

Figure 2. Typical I/O circuit with a floating rail

3 What is injection current?

Any time the voltage on a pin goes either above or below the power supply voltage powering that pin, current is injected into or out of the MCU.

In addition to the case where no current is injected, there are two types/ranges of injection current that are discussed in this application note:

- Voltages that are greater than 0.3 V above the power supply voltage that are externally current limited. In this case, the voltage will be limited by on-chip diodes that will limit the voltage that is seen on the internal input circuitry.
- Voltages that are more than 0.3 V above power supply voltage that are not externally current limited. This also applies to voltages lower than –0.3 V below the ground reference that are not externally current limited.

It should be noted that the most typical example of injection current occurs when the input voltage to a pin goes above the actual power supply voltage that powers the pin. For most automotive MCUs, the I/O pins are powered by nominal 5.0 V supply with a ±10% tolerance (4.50 V to 5.50 V). However, some automotive MCUs limit the voltage to 5.25 V (+5%) only.

NOTE

It is highly recommended that the power supply voltage be limited to 5.25 V on all automotive devices, regardless of the maximum operating voltage of the device. This allows more margin for injection current.

3.1 No injection current

Voltages applied to an MCU I/O pin between the ground reference (VSS) minus 0.3 volts and the power supply voltage (VDD) plus 0.3 volts do not cause any injection currents. Therefore, nothing special needs to be done to pins that do not ever have voltages outside these limits.

3.2 Externally limiting injection current

In cases where the input voltage is expected to be higher than the supply voltage on the input, external circuitry should be added to limit the current to protect the MCU input. In most cases, only a series resistor is required. For some cases, a resistor divider may be used. The external resistors should be sized based on two criteria:

- Constant or typical injected current. The resistor needs to be sized to ensure that the average current injected into a pin is lower than the recommended maximum operating injection current specification in the device data sheet. It is always better to maintain the lowest possible current when injecting a constant current. 1 mA is a good generic maximum current.
- Spurious voltages. Overload conditions are expected on many inputs to the MCU; usually these are due to an error condition. The current limiting resistor should also be sized for the maximum voltage that is expected on the input to the resistor.

A commonly used circuit is shown in the following figure that shows a switch to ground with a pullup resistor to the battery.

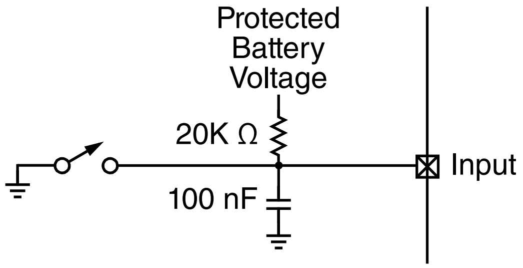

Figure 3. Typical minimum external current liming protection network

These are calculations for a typical worst case scenario; they may need to be modified for the exact expected conditions for a given system. The worst case scenario is when the power supplies are turned off. During operation, the I/O worst case power supply voltage should be used for this calculation.

The value of a series resistor to limit the injected current can be calculated simply. For a 1 mA injection current limit, a 20K Ω resistor provides protection for a typical 20 V DC injection current:

$DC_{max\_unpowered}$ = 20 kΩ x 1 mA = 20 V

$DC_{max\_powered}$ = 20 kΩ x 1 mA + 5.25 = 25.25 V

This voltage is sufficient for MCU pins that are connected to external signals that are pulled up (through a resistor) to a typical 12 V battery.

In addition to the DC current, typically the data sheet includes a maximum accumulation specification for short periods of time over this DC level, such as 5 mA for up to 60 hours over the entire life of the device. (Again, the worst case is shown for the unpowered state.)

$AC_{max\_current}$ = 20 kΩ x 5 mA = 100 V

For example, a typical situation requires some excursions for short durations over the 1 mA (or 2 mA) specification, either from an error condition or another condition. If there are 5 ms excursion events over the 1 mA injection current limit of up to 5 mA, then a total of 43.2K events can occur over the lifetime of the device.

$AC_{max\_duration}$ = 60 hours/5 ms per event = (60 hours x 60 minutes/hour x 60 seconds/minute) / 5 ms = 43,200,000 events

If a greater number of excursions or the voltage of the excursions is different than this typical case, the resistor value may need to be increased or could be decreased.

Another common circuit used with MCUs is shown in the next figure and includes a voltage divider circuit for biasing an external sensor.

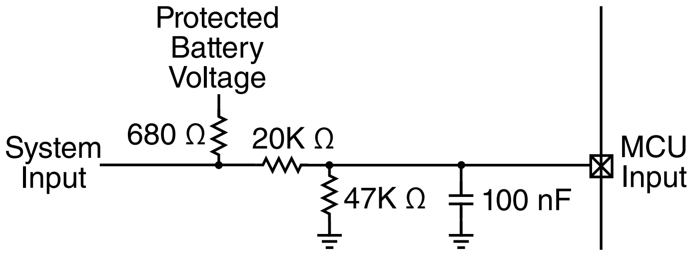

Figure 4. Alternate input protection circuit

3.3 Injection due to overshoot

In some cases, particularly for devices with data and address buses, differences in impedance of the connected devices cause overshoot and undershoot of the supply voltages by the output signals from the memory (or from another external device input to the MCU). It is best to try to match the drive and impedance, but most memory devices that are connected to a MCU bus do not have a drive strength or impedance control. On devices with buses, there is normally an allowable overshoot specification for the I/O pins in the data sheet that is limited by a time duration over the entire lifetime of the device. During this type of overshoot condition, no current limit is required and is acceptable for this limited time over the life of the device.

For example, if the worst case overshoot of the Input pin (above the power supply voltage) when reading from an external memory is 2 V for a duration of 1 ns per read, then with a lifetime specification of 60 hours, this would equate to:

$AC_{max\_duration}$ = 60 hours / 1 ns per read, then the maximum reads would be 2.16 x 10^{14} reads of the memory.

4 Considerations for analog input injection

Current injection on an analog input pin has additional concerns. Injection current can cause a degradation in the accuracy of the Analog-to-Digital Converter (ADC); see the device electrical specifications. In addition, current injection on an analog input may cause errors in adjacent analog channels. The amount of current that causes adjacent channel disruption is also shown in the device data sheet.

NOTE

In general, on Quad Flat Pack (QFP) packages, the adjacent channels are the channels on adjacent leads of the package. However, on Ball Grid Array (BGA) packages, the adjacent channels may not be physically next to the analog input ball due to the routing of the signals on the substrate of the package. The adjacent channels are the adjacent channels on the die pad ring.

NOTE

Adjacent pins may include digital pins. Injection current on adjacent digital signals must also be taken into account for the analog pins and could affect the accuracy of the ADC.

5 Data sheet specifications for injection current

There are several pieces of information in the device data sheet (electrical specifications) that need to be considered and that affect the current injection of a device. This information comes from primarily two sections of the data sheet. The following important specifications from the absolute maximum ratings table:

- Absolute maximum power supply voltage for each power supply

- Absolute maximum injection current
- Maximum input voltage on a pin

The other critical section of the data sheet is the recommended operating specifications, including the following information:.

- Maximum recommended power supply voltage
- Nominal maximum allowable injection current

Some devices handle the inject current on analog inputs in a section of the data sheet separate from the digital pins, but other devices include the analog pin specifications in the same table as the digital pins.

The absolute maximum ratings table of the data sheet includes the maximum spurious conditions for the maximum power supply voltages (surges), the maximum input voltage for pins, and the maximum overload currents allowed for injection.

The recommended operating conditions table of the device data sheet contains information about the nominal operation of the device. This includes the minimum and maximum operating voltages, the nominal input voltages, and the nominal current injection voltage. Conditions outside the nominal operating conditions are considered spurious conditions.

6 Example Data Sheet Excerpts and Measurement Data

Since there are a many different device types in different wafer processing technologies and automotive market spaces, it is not possible to summarize them all. However, this application note includes several examples to demonstrate how to interpret both the data sheet specifications and actual typical device measurements for internal clamp diodes with varying injected current.

These examples show devices from a 16-bit S12 body device (MC9S12DP256), a 130 nm 32-bit powertrain device (MPC5554), two c90 32-bit powertrain devices (MPC5674F/MPC5676R), and a c90 32-bit chassis device (MPC5604B).

NOTE

The following sections contain data sheet excerpts that are intended for illustration only. You should consult nxp.com for the most recent revision of any of data sheet referenced in this document.

6.1 S12 Example

The S12 family of microcontrollers are 16-bit microcontrollers designed in multiple process technologies and for multiple types of applications including body, chassis, and low-end powertrain.

6.1.1 S12 data sheet specifications

The table below shows an extract of the absolute maximum ratings and injection current specifications from the MC9S12DP256 Data Sheet (Version 02.15, dated Jan 11, 2005, Table A-1) and the other S12 families, including the S12XE families.

Absolute maximum ratings are stress ratings only. A functional operation under or outside those maxima is not guaranteed. Stress beyond those limits may affect the reliability or cause permanent damage to the device.

This device contains circuitry that protects against damage due to high static voltage or electrical fields; however, it is advised that normal precautions be taken to avoid application of any voltages higher than maximum-rated voltages to this high-impedance circuit. Reliability of operation is enhanced if unused inputs are tied to an appropriate logic voltage level (for example, either V_{SS5} or V_{DD5}).

Table 3. Selected MC9S12DP256 specifications—Absolute Maximum Ratings

Number	Rating	Symbol	Minimum	Maximum	Unit
1	I/O, Regulator and Analog Supply Voltage	V_{DD5}	–0.3	6.0	V
6	Digital I/O Input Voltage	V_{IN}	–0.3	6.0	V
10	Instantaneous Maximum Current Single pin limit for all digital I/O pins[1]	I_D	–25	25	mA

1. All digital I/O pins are internally clamped to V_{SSX} and V_{DDX}, V_{SSR} and V_{DDR} or V_{SSA} and V_{DDA}.

The table below describes the operating voltage of the device from Table A-4 of the electrical characteristics.

Table 4. Selected MC9S12DP256 specifications—Operating Conditions

Number	Rating	Symbol	Minimum	Maximum	Unit
1	I/O, Regulator and Analog Supply Voltage	V_{DD5}	4.5	5.25	V

The table below shows an extract of Table A-6, I/O Characteristics showing the recommended input voltages and injection current specifications.

Table 5. Selected MC9S12DP256 specifications—5 V I/O Characteristics

Number	Rating	Symbol	Minimum	Maximum	Unit
1	Input High Voltage	V_{IH}	0.65 × VDD5	VDD5 + 0.3	V
2	Input Low Voltage	V_{IL}	VSS – 0.3	0.35 × VDD5	V
12	Injection Current[1] Single Pin limit	I_{ICS}	–2.5	2.5	mA
	Injection Current Total Device Limit. Sum of all injected currents	I_{ICP}	–25	25	mA

1. Power supply must maintain regulation within operating V_{DD5} or V_{DD} range during instantaneous and operating maximum current conditions. If positive injection current (Vin>VDD5) is greater than IDD5, the injection current may flow out of VDD5 and could result in the external power supply going out of regulation. Ensure external VDD5 load will shunt current greater than maximum injection current. This will be the greatest risk when the MCU is not consuming power; e.g. if no system clock is present, or if clock rate is very low which would reduce overall power consumption.

6.1.2 S12 actual typical injection current curves

The figure below shows the voltage to which the pin is limited by the internal input diodes versus the current being injected into the pin. This figure is for a typical MC9S12DP256 pin. In this case, Port A0 is shown.

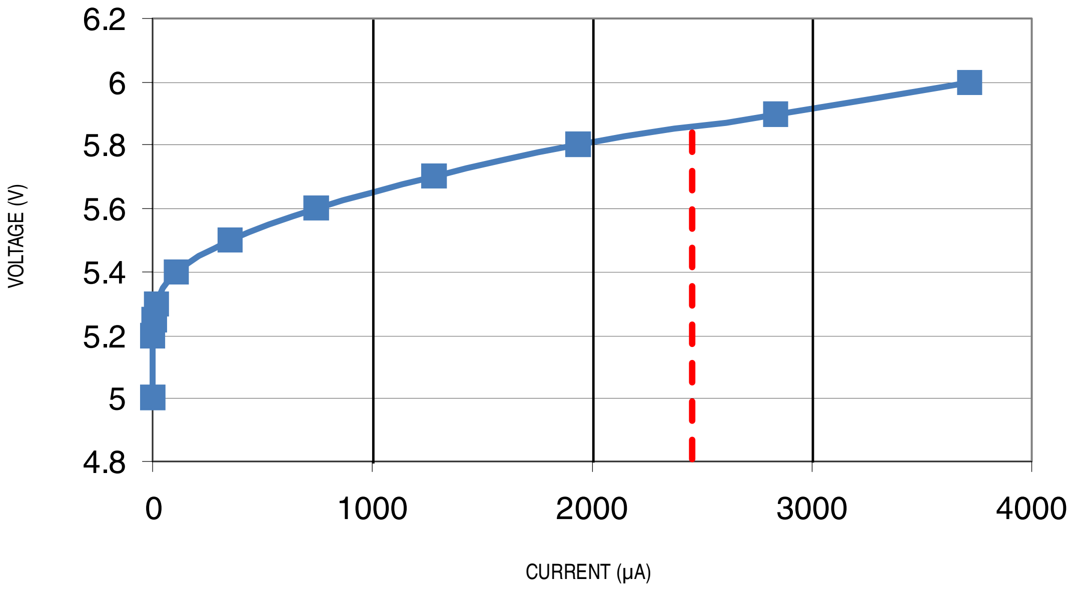

Figure 5. MC9S12DP256 Port A0 injection current versus voltage, 25°C, V_{DD} = 5 V

As shown in this figure, 2 mA of injection current keeps the voltage on the pin below the Absolute Maximum Rating of 6.0 volts. However, if a voltage of 6 V is placed on the pin, the injection current would be approximately 3.75 mA.

6.2 MPC5554 example

The MPC5554 was the first of the e200z6 MCUs fabricated in the 130 nm CMOS wafer process. This device has been in high volume production for several years.

6.2.1 MPC5554 data sheet specifications

Below is an extract from the MPC5554 Data Sheet revision 4, dated May 2012.

Table 6. MPC5554 absolute maximum ratings extract

Specification	Characteristic	Symbol	Minimum	Maximum	Unit
7	3.3 V I/O buffer voltage	V_{DD33}	–0.3	4.6	V
10	I/O supply voltage (fast I/O pads)[1]	V_{DDE}	–0.3	4.6	V
11	I/O Supply Voltage (slow and medium I/O pads)[1]	V_{DDEH}	–0.3	6.5	V
12	DC Input voltage[2] V_{DDEH} powered I/O pads V_{DDE} powered I/O pads	V_{IN}	–1.0[3] –1.0[3]	6.5[4] 4.6[5]	V
24	Maximum DC Digital Input Current[6] (per pin, applies to all digital pins)[2]	I_{MAXD}	–2	2	mA
25	Maximum DC analog Input Current[7] (per pin, applies to all digital pins)	I_{MAXA}	–2	2	mA

Table continues on the next page...

Table 6. MPC5554 absolute maximum ratings extract (continued)

Specification	Characteristic	Symbol	Minimum	Maximum	Unit
26	Maximum Operating Temperature range[8] - Die junction temperature	T_J	T_L[9]	150.0	°C

1. All functional non-supply I/O pins are clamped to V_{SS} and V_{DDE}, or V_{DDEH}.
2. AC signal overshoot and undershoot of up to ± 2.0 V of the input voltages is permitted for an accumulative duration of 60 hours over the complete lifetime of the device (injection current not limited for this duration).
3. Internal structures hold the voltage greater than –1.0 V if the injection current limit of 2 mA is met. Keep the negative DC voltage greater than –0.6 V on eTPUB[15] and SINB during the internal power-on reset (POR) state.
4. Internal structures hold the input voltage less than the maximum voltage on all pads powered by VDDEH supplies, if the maximum injection current specification is met (2 mA for all pins) and VDDEH is within the operating voltage specifications.
5. Internal structures hold the input voltage less than the maximum voltage on all pads powered by VDDE supplies, if the maximum injection current specification is met (2 mA for all pins) and VDDE is within the operating voltage specifications.
6. Total injection current for all pins (including both digital and analog) must not exceed 25 mA.
7. Total injection current for all analog input pins must not exceed 15 mA.
8. Lifetime operation at these specification limits is not guaranteed.
9. –40°C or -55°C depending on part number ordered.

The table below describes the operating voltage of the MPC5554 from the DC electrical specifications table.

Table 7. Selected MPC5554 specifications—Operating Conditions

Number	Rating	Symbol	Minimum	Maximum	Unit
2	I/O Supply Voltage (fast I/O pads)[1]	V_{DDE}	1.62	3.6	V
3	I/O Supply Voltage (slow and medium I/O pads)	V_{DDEH}	3.0	5.25	V
4	3.3 V input/output buffer voltage	V_{DD33}	3.0	3.6	V
6	Analog Supply Voltage[2]	V_{DDA}	4.50	5.25	V
12	Fast I/O input high voltage	V_{IH_F}	$0.65 \times V_{DDE}$	$V_{DDE} + 0.3$	V
13	Fast I/O input low voltage	V_{IL_F}	$V_{SS} – 0.3$	$0.35 \times V_{DDE}$	V
14	Medium and slow I/O input high voltage	V_{IH_S}	$0.65 \times V_{DDEH}$	$V_{DDEH} + 0.3$	V
15	Medium and slow I/O input low voltage	V_{IL_S}	$V_{SS} – 0.3$	$0.35 \times V_{DDE}$	V
18	Analog input voltage	V_{INDC}	$V_{SSA} – 0.3$	$V_{DDA} + 0.3$	V
34	DC injection current (per pin)	I_{IC}	–2.0	2.0	mA

1. VDDE2 and VDDE3 are limited to 2.25–3.6 V only if SIU_ECCR[EBTS] = 0; VDDE2 and VDDE3 have a range of 1.62–3.6 V if SIU_ECCR[EBTS] = 1.
2. | VDDA0 – VDDA1 | must be < 0.1 V

The recommended operating electrical specifications also include some information about the injection current. These are the currents

Table 8. MPC5554 additional analog specifications

Pin type	Maximum inject current allowed		Minimum	Maximum	Unit
13[1]	Disruptive Input Current for Analog Pins[2, 3, 4, 5]		–1	1	mA

Table continues on the next page...

Table 8. MPC5554 additional analog specifications (continued)

Pin type	Maximum inject current allowed		Minimum	Maximum	Unit
12	Incremental error due to injection current. All channels are 10 kΩ < Rs <100 kΩ Channel under test has Rs = 10 kΩ $I_{INJ} = I_{INJMAX}, I_{INJMIN}$	E_{INJ}	–4	4	Counts

1. eQADC Conversion Specifications (Operating) table
2. Below disruptive current conditions, the channel being stressed has conversion values of: 0x3FF for analog inputs greater than V_{RH}, and 0x000 for values less than V_{RL}. This assumes that $V_{RH} \leq V_{DDA}$ and $V_{RL} \geq V_{SSA}$ due to the presence of the sample amplifier. Other channels are not affected by non-disruptive conditions.
3. Exceeding the limit can cause a conversion error on both stressed and unstressed channels. Transitions within the limit do not affect device reliability or cause permanent damage.
4. Input must be current limited to the value specified. To determine the value of the required current-limiting resistor, calculate resistance values using $V_{POSCLAMP} = V_{DDA} + 0.5$ V and $V_{NEGCLAMP} = -0.3$ V, then use the larger of the calculated values.
5. This condition applies to two adjacent pads on the internal pad.

6.2.2 MPC5554 actual typical injection current measurements

The figure below shows the voltage to which the pin is limited versus the current being injected into the pin for a slow speed high voltage digital pin. The data in the below figure is for the MPC5554 EMIOS14_GPIO203 pin.

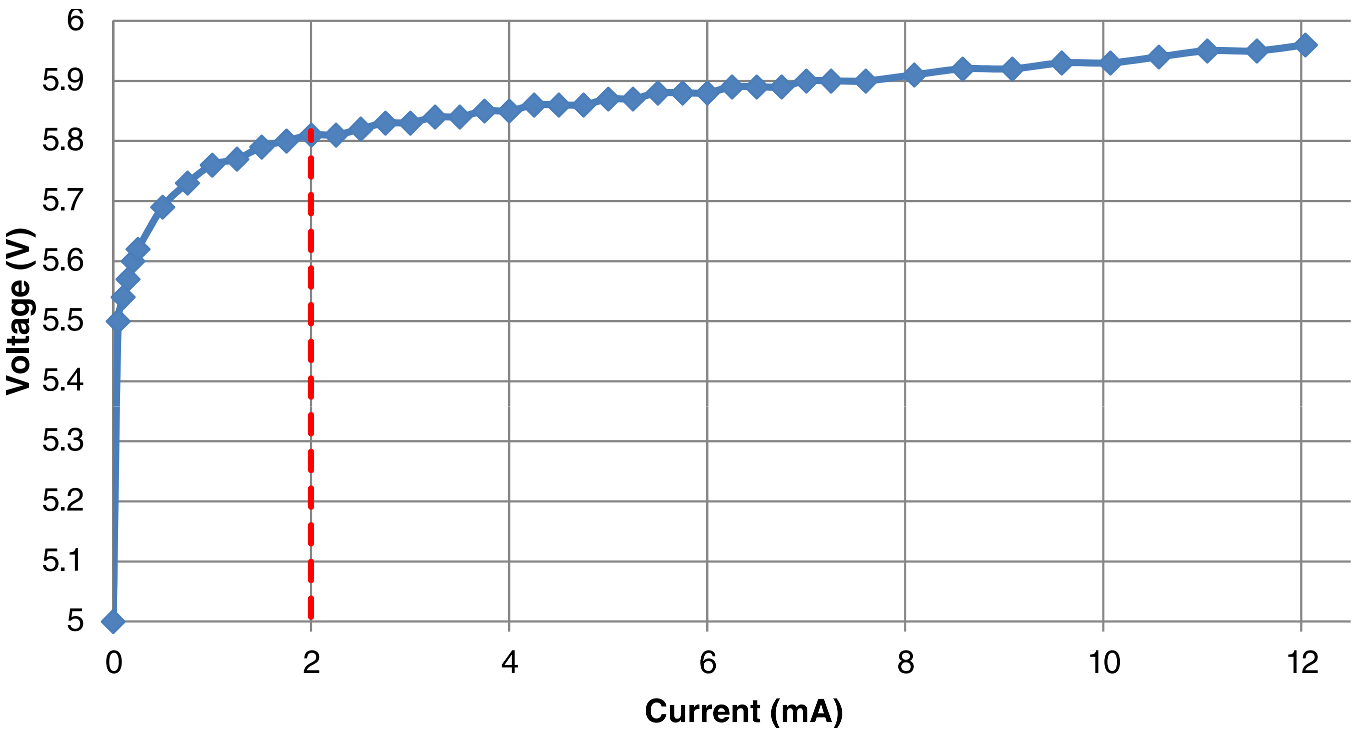

Figure 6. MPC5554 pin GPIO[203] digital pin injection current versus voltage, 25°C, V_{DDEH} = 5V

As shown in this figure, almost no current is injected when the voltage applied to the pin is up to approximately 0.5 V above the supply voltage. 2 mA of injection current keeps the voltage on the pin less than the Absolute Maximum Rating of 6.4 V as long as the power supply is less than 5.5 V. A 5.25 maximum supply voltage is recommended.

6.3 MPC567xF/MPC5676R example

The MPC567xF and MPC5676R are higher end processors fabricated in the c90 CMOS wafer process; both are intended primarily for powertrain applications. The MPC567xF is a single-core microcontroller and the MPC5676R is a dual-core MCU. Both devices include an enhanced Timing Processing Unit (eTPU).

6.3.1 MPC5674F and MPC5676R data sheet specifications

Although the MPC5674F and the MPC5676R data sheets appear to be different, when analyzed with their footnotes, they actually are specified the same. The MPC5674F specifies a maximum voltage on the digital I/O pins of 6.4 V, with a footnote that limits the accumulated duration over the life of the device to 10 hours (at 6.4 V) and the rest of the operating time should be at 5.5 V or less. The MPC5676R specifies a maximum voltage of 5.5 V over the operating life of the device, with up to 10 hours of excursions up to 6.4 V accumulated over the life of the device.

Below is an extract from the MPC5674F Data Sheet revision 9, dated 11/2012. These specifications may change.

Table 9. MPC5674F absolute maximum ratings extract

Specification	Characteristic	Symbol	Minimum	Maximum	Unit
4	I/O Supply Voltage (I/O buffers and predrivers) {This is a nominal 3.3 V supply.}	V_{DD33}	–0.3	5.3[1],[2]	V
6	I/O Supply Voltage (fast I/O pads) {This is a nominal 3.3 V supply. }	V_{DDE}	–0.3	5.3[1,2]	V
7	I/O Supply Voltage (medium I/O pads) {This is a nominal 3.3 V or 5 V supply.}	V_{DDEH}	–0.3	6.4[3]	V
15	Absolute Maximum Digital Input Current[4] (per pin, applies to all digital pins)	I_{MAXD}	–3[5]	3[5]	mA
16	Absolute Maximum Input Current, Analog Pins[6] (per pin, applies to all digital pins)	I_{MAXA}	–3[5]	3[5]	mA
17	Maximum Operating Temperature range[7] - Die junction temperature	T_J	–40.0	150.0	°C

1. Voltage overshoots during a high-to-low or low-to-high transition must not exceed 10 seconds per instance.
2. 5.3 V for 10 hours cumulative time, 3.3V +10% for time remaining.
3. 6.4 V for 10 hours cumulative time, 5.0V +10% for time remaining.
4. Total injection current for all pins must not exceed 25 mA at maximum operating voltage.
5. Injection current of ±5 mA allowed for limited duration for analog (ADC) pads and digital 5 V pads. The maximum accumulated time at this current shall be 60 hours. This includes an assumption of a 5.25 V maximum analog or VDDEH supply when under this stress condition.
6. Total injection current for all analog input pins must not exceed 15 mA.
7. Lifetime operation at these specification limits is not guaranteed.

The table below describes the operating voltage of the MPC567xF from the DC electrical specifications table.

Table 10. Selected MPC5674F specifications—Operating Conditions

Number	Rating	Symbol	Minimum	Maximum	Unit
2	I/O Supply Voltage (fast I/O pads)	V_{DDE}	3.0	3.6[1, 2]	V
3	I/O Supply Voltage (medium I/O pads)	V_{DDEH}	3.0	5.25[3]	V
5	Analog Supply Voltage	V_{DDA}	4.75	5.25[3]	V
9	Fast I/O Input High Voltage Hysteresis enabled Hysteresis disabled	VIH_F	$0.65 \times V_{DDE}$ $0.55 \times V_{DDE}$	VDDE + 0.3	V
10	Fast I/O Input Low Voltage Hysteresis enabled Hysteresis disabled	VIH_L	VSS – 0.3	0.35 × VDDE 0.40 × VDDE	V
11[3]	Medium I/O Input High Voltage Hysteresis enabled Hysteresis disabled	VIH_S	$0.65 \times V_{DDE}$ $0.55 \times V_{DDE}$	VDDE + 0.3	V
12	Medium I/O Input Low Voltage Hysteresis enabled Hysteresis disabled	VIL_S	VSS – 0.3	0.35 × VDDE 0.40 × VDDE	V

1. Voltage overshoots during a high-to-low or low-to-high transition must not exceed 10 seconds per instance.
2. 5.3 V for 10 hours cumulative time, 3.3 V +10% for time remaining.
3. 6.4 V for 10 hours cumulative time, 5.0 V +10% for time remaining.

The recommended operating electrical specifications also include some information about the injection current, as shown in the table below.

Table 11. MPC5674F additional injection/input currents allowed

Pin type	Maximum inject current allowed	Symbol	Minimum	Maximum	Unit
31[1]	DC Injection Current (per pin)	I_{IC}	–1	1	mA
13[2]	Disruptive Input Current for Analog Pins[3, 4, 5, 6]	I_{INJ}	–3	3	mA
14[2]	Incremental Error due to Injection current[7]	E_{INJ}	–4	4	Counts

1. DC Electrical Specifications table
2. eQADC Conversion Specifications (Operating) table
3. Below disruptive current conditions, the channel being stressed has conversion values of 0x3FF for analog inputs greater than V_{RH} and 0x000 for values less than V_{RL} . Other channels are not affected by non-disruptive conditions.
4. Exceeding limit may cause conversion error on stressed channels and on unstressed channels. Transitions within the limit do not affect device reliability or cause permanent damage.
5. Input must be current limited to the value specified. To determine the value of the required current-limiting resistor, calculate resistance values using $V_{POSCLAMP} = V_{DDA} + 0.5$ V and $V_{NEGCLAMP} = -0.3$ V, then use the larger of the calculated values.
6. Condition applies to two adjacent pins at injection limits. {Note that adjacent channels refers to the die pad locations and may not correspond directly to the ball map of a BGA package.}
7. All channels have same 10 kΩ < Rs < 100 kΩ.Channel under test has Rs = 10 kΩ, $I_{INJ}=I_{INJMAX},I_{INJMIN}$.

The MPC5676R Data Sheet extracts (revision 3, dated December 2011) are shown in the following tables.

Table 12. MPC5676R absolute maximum ratings

Specification	Characteristic	Symbol	Minimum	Maximum	Unit
4	I/O Supply Voltage (I/O buffers and predrivers)	V_{DD33}	–0.3	4.5[1],[2]	V
5	Analog Supply (reference to VSSA[3])	VDDA[4]	–0.3	5.5[1,5]	V
6	I/O Supply Voltage (fast I/O pads)	V_{DDE}	–0.3	4.5[1]	V
7	I/O Supply Voltage (medium I/O pads)	V_{DDEH}	–0.3	5.5[5]	V
15	Absolute Maximum Digital Input Current[6] (per pin, applies to all digital pins)	I_{MAXD}	–3[7]	3[7]	mA
16	Absolute Maximum Input Current, Analog Pins[8] (per pin, applies to all digital pins)	I_{MAXA}	–3[7]	3[7]	mA
17	Maximum Operating Temperature range[9]—Die junction temperature	T_J	–40.0	150.0	°C

1. Voltage overshoots during a high-to-low or low-to-high transition must not exceed 10 seconds per instance.
2. 5.3 V for 10 hours cumulative time, 3.3V +10% for time remaining.
3. MPC5676R has two analog ground pins on the pin-out: VSSA_A and VSSA_B
4. MPC5676R has two analog power supply pins on the pin-out: VDDA_A and VDDA_B
5. 6.4 V for 10 hours cumulative time, 5.0V +10% for time remaining.
6. Total injection current for all pins must not exceed 25 mA at maximum operating voltage.
7. Injection current of ±5 mA allowed for limited duration for analog (ADC) pads and digital 5 V pads. The maximum accumulated time at this current shall be 60 hours. This includes an assumption of a 5.25 V maximum analog or VDDEH supply when under this stress condition.
8. Total injection current for all analog input pins must not exceed 15 mA.
9. Lifetime operation at these specification limits is not guaranteed.

The table below describes the operating voltage of the MPC5676R from the DC electrical specifications table.

Table 13. Selected MPC5676R specifications—Operating Conditions

Number	Rating	Symbol	Minimum	Maximum	Unit
2	I/O Supply Voltage (fast I/O pads)	V_{DDE}	3.0	3.6[1]	V
3	I/O Supply Voltage (medium I/O pads)	V_{DDEH}	3.0	5.25[1]	V
5	Analog Supply Voltage	V_{DDA}	4.75	5.25[1]	V
9	Fast I/O Input High Voltage Hysteresis enabled Hysteresis disabled	VIH_F	 $0.65 \times V_{DDE}$ $0.55 \times V_{DDE}$	VDDE + 0.3	V
10	Fast I/O Input Low Voltage Hysteresis enabled Hysteresis disabled	VIH_L	VSS – 0.3	 $0.35 \times V_{DDE}$ $0.40 \times V_{DDE}$	V
11	Medium I/O Input High Voltage Hysteresis enabled Hysteresis disabled	VIH_S	 $0.65 \times V_{DDEH}$ $0.55 \times V_{DDEH}$	$V_{DDE} + 0.3$	V

Table continues on the next page...

Table 13. Selected MPC5676R specifications—Operating Conditions (continued)

Number	Rating	Symbol	Minimum	Maximum	Unit
12	Medium I/O Input Low Voltage Hysteresis enabled Hysteresis disabled	VIL_S	VSS – 0.3	0.35 x V_{DDE} 0.40 x V_{DDE}	V

1. Voltage overshoots during a high-to-low or low-to-high transition must not exceed 10 seconds per instance.

Table 14. MPC5676R additional injection/input currents allowed

Pin type	Maximum inject current allowed	Symbol	Minimum	Maximum	Unit
31[1]	DC Injection Current (per pin)	I_{IC}	–1	1	mA
13[2]	Disruptive Input Current for Analog Pins[3, 4, 5, 6]	I_{INJ}	–3	3	mA
14[2]	Incremental Error due to Injection current[7]	E_{INJ}	–4	4	Counts

1. DC Electrical Specifications table
2. eQADC Conversion Specifications (Operating) table
3. Below disruptive current conditions, the channel being stressed has conversion values of 0x3FF for analog inputs greater than V_{RH} and 0x000 for values less than V_{RL}. Other channels are not affected by non-disruptive conditions.
4. Exceeding limit may cause conversion error on stressed channels and on unstressed channels. Transitions within the limit do not affect device reliability or cause permanent damage.
5. Input must be current limited to the value specified. To determine the value of the required current-limiting resistor, calculate resistance values using $V_{POSCLAMP}$ =V_{DDA} + 0.5 V and $V_{NEGCLAMP}$ = –0.3 V, then use the larger of the calculated values.
6. Condition applies to two adjacent pins at injection limits. {Note that adjacent channels refers to the die pad locations and may not correspond directly to the ball map of a BGA package.}
7. All channels have same 10 kΩ < Rs < 100 kΩ.Channel under test has Rs = 10 kΩ, I_{INJ}=I_{INJMAX},I_{INJMIN}.

6.3.2 MPC567xF and MPC5676R actual typical injection current measurements

The figure below shows the voltage to which the pin is limited versus the current being injected into the pin for a medium speed high voltage digital pin. The data in the below figure is for the MPC567xF EMIOS9_ETPUA9_GPIO188 pin. Lines are shown at the different limits for current injection (1 mA recommended operating conditions, normal 3 mA absolute maximum rating, and 5 mA absolute maximum rating for a limited duration).

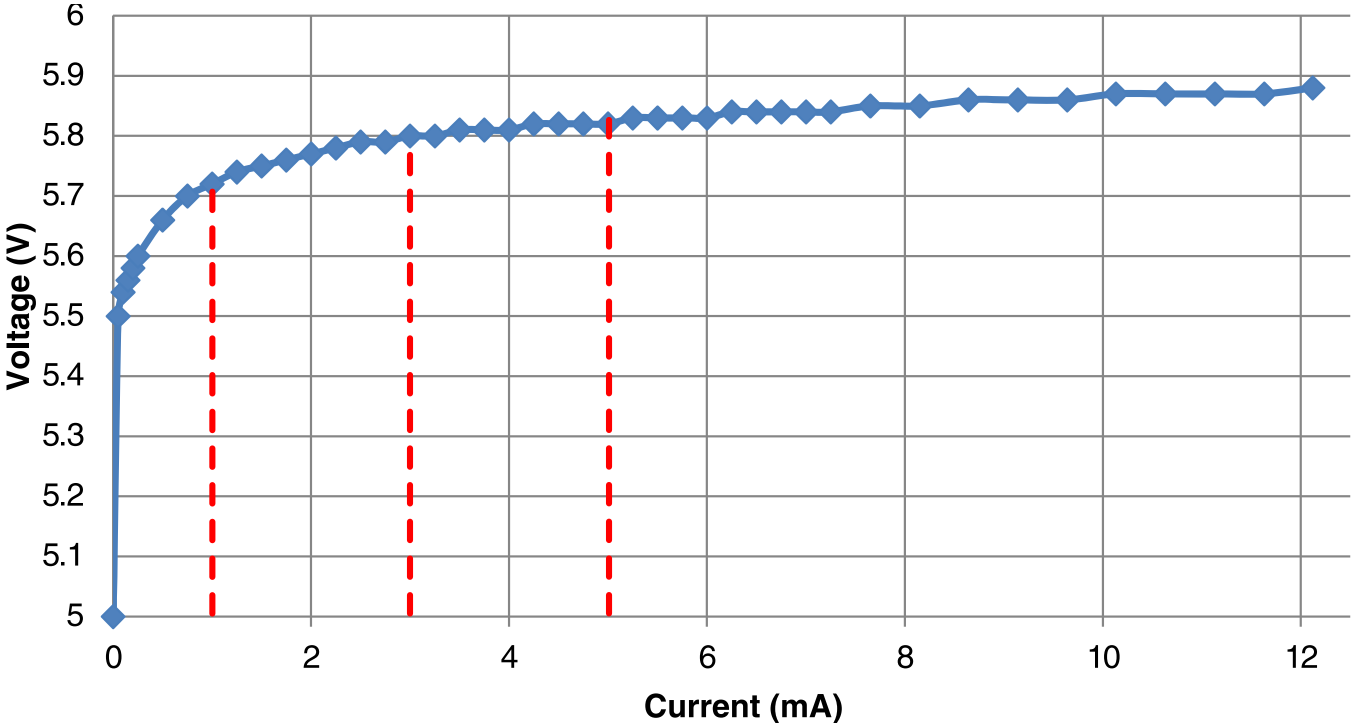

Figure 7. MPC567xF pin GPIO[188] digital pin injection current versus voltage, 25°C, V_{DDEH} = 5V

Data from a typical analog pin (ANA0) is shown in the figure below.

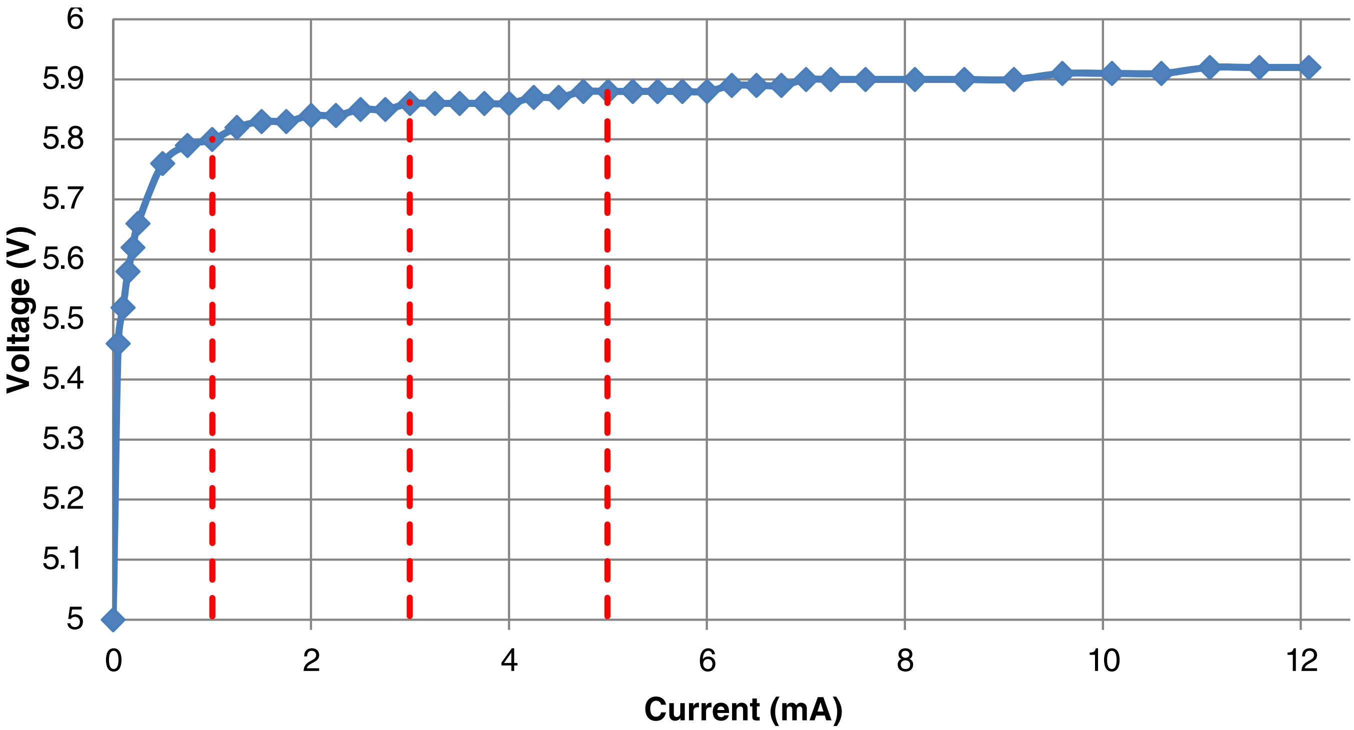

Figure 8. MPC567xF pin ANA0 analog pin injection current versus voltage, 25°C, V_{DDEH} = 5V

As shown in these two figures, almost no current is injected when the voltage applied to the pin is up to approximately 0.5 V above the supply voltage. 2 mA of injection current keeps the voltage on the pin less than the absolute maximum rating of 6.4 V as long as the power supply is less than 5.5 V. A 5.25 maximum supply voltage is recommended.

6.4 MPC56xxB/C/D example

The MPC56xxB/C/DC microcontrollers are intended primarily for the body/chassis market and are fabricated in the c90 CMOS wafer process. This family ranges from the low end MPC5602D to the higher end MPC5646C. The I/O electrical characteristics are the same throughout the family of devices.

Table 15. MPC56xxB/C/D family devices

Device
MPC5601D
MPC5602D
MPC5603B
MPC5603C
MPC5604B
MPC5604C
MPC5605B
MPC5606B
MPC5607B
MPC5644B
MPC5644C
MPC5645B
MPC5646B
MPC5646C

6.4.1 MPC56xxB/C/D data sheet specifications

Below is an extract from the MPC5604B Data Sheet revision 11, dated 12/2012. All devices in the MPC56xxB/C/D family have similar electrical characteristics. These specifications may change. Consult the latest revision of the data sheet to determine if there have been updates to these specifications.

Table 16. MPC56046B absolute maximum ratings

Parameter	Symbol	Conditions	Minimum	Maximum	Unit
Digital ground on VSS_HV pins	V_{SS_HV}	—	0	0	V
Voltage (on VDD_HV pins with respect to ground (V_{SS})	V_{DD}	—	–0.3	6.0	V
Voltage on VSS_LV (low voltage digital supply) pins with respect to ground (V SS_HV)	V_{SS_LV}	—	V_{SS} – 0.1	V_{SS} + 0.1	V

Table continues on the next page...

Table 16. MPC56046B absolute maximum ratings (continued)

Parameter	Symbol	Conditions	Minimum	Maximum	Unit
Voltage on VDD_BV pin (regulator supply) with respect to ground (V_{SS})	V_{DD_BV}	—	–0.3	6.0	V
		Relative to V_{DD}	–0.3	VDD + 0.3	
Voltage on VSS_HV_ADC (ADC reference) pin with respect to ground (V_{SS_HV})	V_{SS_ADC}	—	V_{SS} – 0.1	V_{SS} + 0.1	V
Voltage on VDD_HV_ADC (ADC reference) with respect to ground (V_{SS})	V_{DD_ADC}	—	–0.3	6.0	V
		Relative to V_{DD}	V_{DD} – 0.3	V_{DD} + 0.3	V
Voltage on any GPIO pin with respect to ground)	V_{IN}	—	V_{DD} – 0.3	6.0	V
		Relative to V_{DD}	—	V_{DD} + 0.3	
Injected input current on any pin during overload condition	I_{INJPAD}	—	–10	10	mA
Absolute sum of all injected input currents during overload condition	I_{INJSUM}	—	–50	50	mA
Sum of all the static I/O current within a supply segment ($V_{DD\_HV\_A}$ or $V_{DD\_HV\_B}$)	I_{AVGSEG}	V_{DD} = 5.0V ± 10%, PAD3V5V = 0	—	70	mA
		V_{DD} = 3.3V ± 10%, PAD3V5V = 1	—	64	
Low voltage static current sink through VDD_BV	I_{CORELV}	—	—	150	mA
Storage temperature	T STORAGE	—	–55[1]	150	°C

1. This is the storage temperature for the flash memory.

In addition, the data sheet includes the following note:

NOTE

Stresses exceeding the recommended absolute maximum ratings may cause permanent damage to the device. This is a stress rating only and functional operation of the device at these or any other conditions above those indicated in the operational sections of this specification are not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability. During overload conditions ($V_{IN} > V_{DD}$ or $V_{IN} < V_{SS}$), the voltage on pins with respect to ground (V_{SS}) must not exceed the recommended values.

Table 17. MPC5604B recommended 3.3 V operating conditions (excerpt)

Pin type	Symbol	Conditions	Value		Units
			Minimum	Maximum	
Digital ground on VSS_HV pins	V_{SS}	—	0	0	V
Voltage on VDD_HV pins with respect to ground (V_{SS})	V_{DD}	—	3.0	3.6	V
Voltage on any GPIO pin with respect to ground (V_{SS_HV})	V_{IN}	—	V_{SS} – 0.1	—	V
		Relative to V_{DD}	—	V_{DD} + 0.1	
Injected input current on any pin during overload condition	I_{INJPAD}	—	–5	5	mA

Table continues on the next page...

Table 17. MPC5604B recommended 3.3 V operating conditions (excerpt) (continued)

Pin type	Symbol	Conditions	Value		Units
			Minimum	Maximum	
Absolute sum of all injected input currents during overload condition	I_{INJSUM}	—	–50	50	

Table 18. MPC5604B recommended 5.0 V operating conditions (excerpt)

Pin type	Symbol	Conditions	Value		Units
			Minimum	Maximum	
Digital ground on VSS_HV pins	V_{SS}	—	0	0	V
Voltage on VDD_HV pins with respect to ground (V_{SS})	V_{DD}	—	4.5	5.5	V
Voltage on any GPIO pin with respect to ground (V_{SS_HV})	V_{IN}	—	V_{SS_HV} – 0.1	—	V
		Relative to V_{DD}	—	V_{DD} + 0.1	
Injected input current on any pin during overload condition	I_{INJPAD}	—	–5	5	mA
Absolute sum of all injected input currents during overload condition	I_{INJSUM}	—	–50	50	

Table 19. MPC5604B ADC conversion characteristics (excerpt)

Pin type	Symbol	Conditions		Value		Units
				Minimum	Maximum	
Input current Injection	I_{INJ}	Current injection on one ADC_0 input, different from the converted one	V_{DD} = 3.3V ±10%	–5	5	mA
			V_{DD} = 5.0V ±10%	–5	5	
Total unadjusted error[1] for precise channels, input only pins	TUEp	Without current injection		–2	2	LSB
		With current injection		–3	3	
Total unadjusted error[1] for extended channel	TUEx	Without current injection		–3	3	LSB
		With current injection		–4	4	

1. Total Unadjusted Error: The maximum error that occurs without adjusting Offset and Gain errors. This error is a combination of Offset, Gain and Integral Linearity errors.

6.4.2 MPC560xB actual typical injection current measurements

The figure below shows the voltage to which the pin is limited versus the current being injected into the pin. This figure is for the MPC5602B Port A, bit 0 (PA0) pin. Lines are shown at the 5 mA maximum recommended operating injection current limit and at 10 mA, the absolute maximum rating for I/O pins.

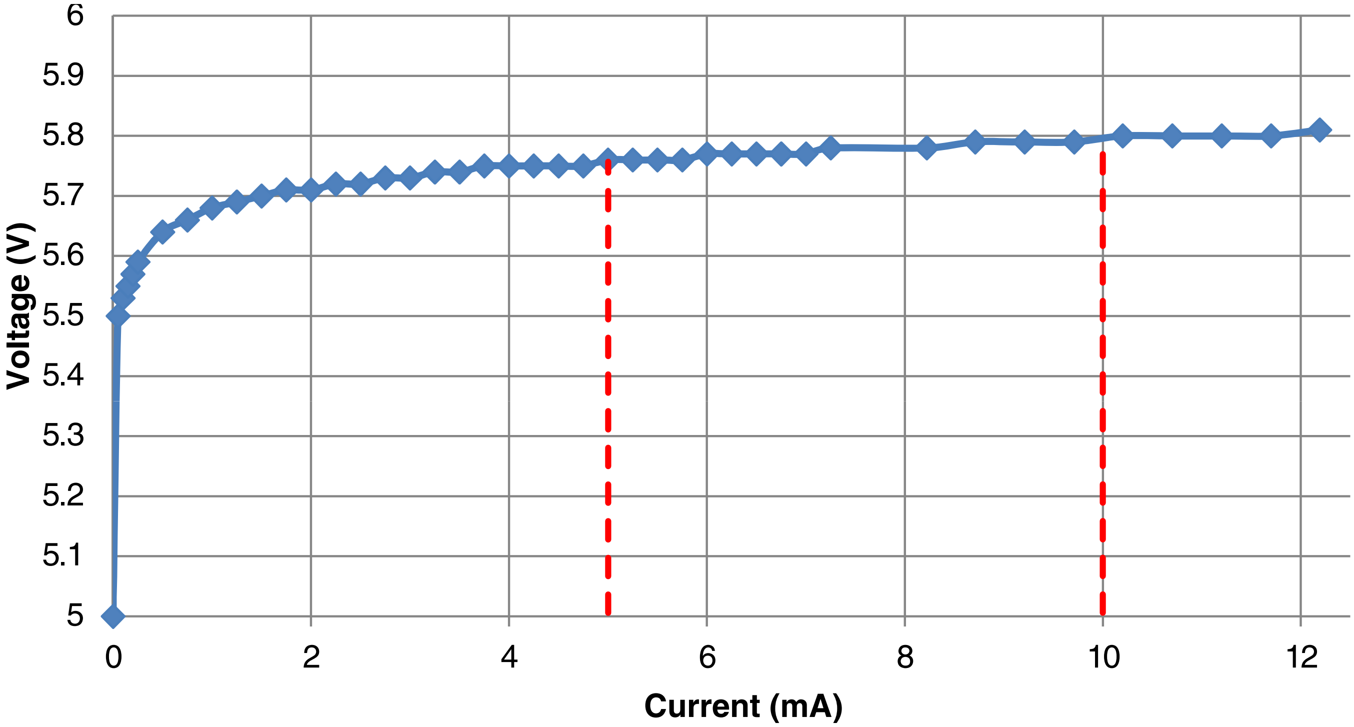

Figure 9. MPC5646C pin PA0 injection current versus voltage, 25°C, V_{DD} = 5V

As shown in this figure, almost no current is injected when the voltage applied up to approximately 0.4 V above the supply voltage. 2.5 mA of injection current keeps the voltage on the pin less than the absolute maximum rating of 6.0 V. A 5.25 maximum supply voltage is recommended.

7 Summary

While there are many factors that affect the handling of injection current in a system, NXP has taken many of these issues into account in the design of its automotive microcontrollers. Internal clamp diodes are included on user I/O pins that limit the exposure of internal circuitry to safe voltages under typical injection current conditions. The typical expected injection currents are specified in the recommended operating conditions of the device data sheet and are generally in the range of 1 to 5 mA. Most devices include additional specifications that allow for excursions above the recommended injection current specifications for short durations of time that is accumulated over the lifetime of the MCU.

You should take care to limit your injection current according to the specifications in the data sheet for each device for both the maximum recommended operating injection current (typical injected current) and for the absolute maximum rating injection current for spurious conditions. Adhering to the specifications will insure the lifetime capability of the system.

Appendix A Temperature Profile

Different types of automotive applications require different lifetime temperature profiles. Some types of applications are more stringent and some are less. These depend on the location of a MCU module within the vehicle. An example of a temperature profile is shown below.

Table A-1. 20 year (175200 hours) typical temperature profile

T_J (°C)	10% Power On Hours	Always Activated hours
	Core logic (I/O, SRAM, High Voltage transistors)	Keep-Alive logic (SRAM)
150	1298	1298
135	5407	5407
125	5407	5407
105	5407	5407
40	0	157680
Total hours on	17520	175200
Effective T_J Ea = 0.5eV	127°C	75°C
Effective T_J Ea = 1.0eV	130°C	100°C

MCUs are designed for an expected temperature profile. Aspects of the design that affect the design include the metal width and sizes of transistors that are connected to the the I/O pins.

Appendix B Revision history

Table B-1. Revision history

Revision	Release Date	Changes
1	06/2013	Initial customer release.
2	12/2017	Corrected formulas in Externally limiting injection current (incorrectly showed division instead of multiplication.
		Added clarification about the unpowered state in the Introduction section.

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