Proposed design for Tempest lighting system

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1 Requirements

We need individual control over headlights, highbeams, left and right indicators, and taillights for 3 hours at a time. In addition, the indicators need to flash at 1.5 Hz to 2 Hz when on, and the taillights need to be dimmable to about half brightness (with the dimmer state the default). We will be using LEDs with the specifications listed in Table 1.

When the system powers up, the head lights and the dimmed tail lights should be on. The indicators have separate momentary switches (usually off). The high beams need a separate on-off switch. The taillights have a momentary switch for full brightness which will be incorporated into the brake system.

Table 1: LED specifications

Light	Number	Voltage (V)	Current (A)	Power (W)	Control	Colour
Headlights	8	3.2 – 3.4	0.35	1	On/off	White
Highbeams	2	2.95 – 3.25	3.00	10	On/off	White
Left indicator	4	2 – 2.2	0.2625	1	On/off, flashing	Yellow
Right indicator	4	2 – 2.2	0.2625	1	On/off, flashing	Yellow
Taillights	8	1.7 – 1.9	0.2625	1	On/off, dimmable	Red

2 Options

We considered several options. The simplest approach is to put a resistor in series with the LEDs. This is not very robust, however, as it does not correct for changes in current or voltage due to supply variation, temperature change, or other factors.

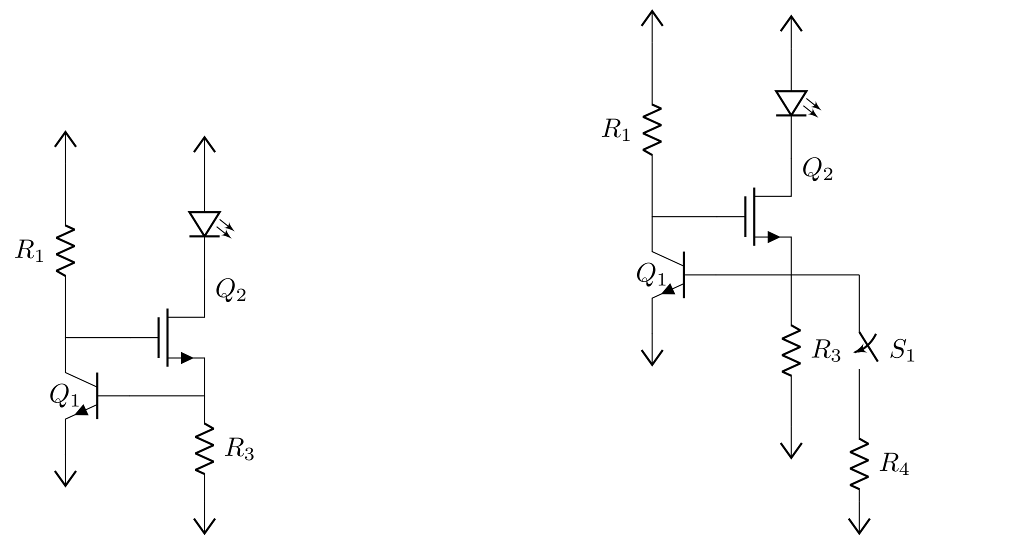
A constant-current driver is preferable. These are available commercially, but are easy enough and much cheaper to make. This is the proposed solution.

3 Proposed solution

3.1 LED drivers

I propose using a constant-current driver. The simplest form of this circuit is given in Figure 1a. Initially, if Q_1 is off, no current flows through R_1, which pulls the gate of Q_2 high, allowing current to flow through the LED, Q_2, and R_3. However, if too much current flows, the voltage at the base of Q_1 increases, which turns this transistor on. Current flows though R_1, reducing the voltage at the gate of Q_2, and the current through the LED is reduced until Q_1 turns back off. Note that the voltage across R_3 stays constant at the threshold voltage of Q_1 (typically about 0.6 V).

I propose using this circuit for the headlights, highbeams and indicators, with switches on the power lines for on/off control. The indicators are powered by a PWM signal in series with the on/off switch. A small variation, show in Figure 1b makes the circuit dimmable by adding a switch which changes the value of R_3, and consequently the steady-state current through the LED.



(a) Constant-current LED driver (b) Constant-current LED driver with dimming

Figure 1: (a) the basic circuit; (b) circuit with switched resistor for dimming.

3.2 PWM circuit

To make the indicators flash, I propose using a 555 timer to output a low-frequency PWM signal. This circuit is shown in Figure 2. The frequency is controlled by the product R_2C_1 (see "Choosing parts" below). The given configuration gives a 50% duty cycle.

4 Implementation

4.1 LED configuration

There are several LEDs for each light. We need to decide how to arrange them (i.e., in series, parallel, or some combination of these). Putting them all in series saves power, since we only have one line drawing current from power to ground. However, each LED needs a certain voltage drop to function (see Table 1), so we cannot necessarily fit them all in series between 9 V or 12 V rails. In addition, each indicator has 2

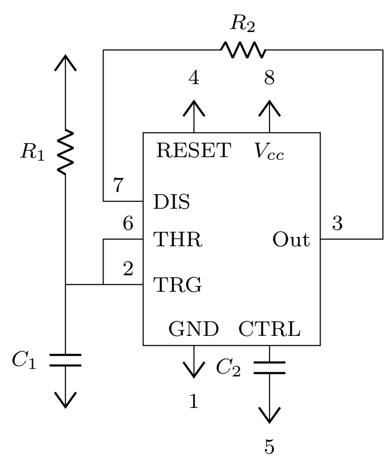


Figure 2: PWM circuit with 555 timer

LEDs at the front of the bike and 2 at the back, which means it is preferable to have an even number of parallel lines in this case (the alternative being to run even more wires inside the bike).

The average voltage drops when the LEDs are split into different numbers of parallel lines are given in Table 2. In each case, each line has the same number of LEDs (less symmetric cases were considered briefly, but didn't alter the given results). The smallest numbers of parallel lines which give voltages under 9 V are bolded (the results do not change for 12 V). The total current corresponding to each of these cases is also given in the table.

Table 2: Average voltage across LEDs for different numbers of parallel lines

Parallel lines	1	2	4	8	Current in chosen case (A)
Headlights	26.4	13.2	**6.6**	3.3	1.4
Highbeams	**6.2**	3.1			3
Left indicator		**4.2**	2.1		0.525
Right indicator		**4.2**	2.1		0.525
Taillights	14.4	**7.2**	3.6	1.8	0.525

In summary, I suggest 4 lines of 2 LEDs each for the headlights, 1 line of 2 LEDs for the highbeams, 2 lines of 4 LEDs each for each indicator (one line each to front and back), and 2 lines of 4 LEDs each for the taillights.

4.2 Choosing parts

4.2.1 Batteries

See Ann's notes. Since we can't fit any more LEDs in series by switching from 9 V to 12 V, I suggest we use 9 V. Calvin suggested lithium iron phosphate, because they don't catch fire but still have good power density.

4.2.2 Transistors

The main requirement for the Q_2 transistors is that they can handle the currents listed in Table 2. I suggest the FQP30N06, which handles up to 32 A, and is cheap and readily available.

These will need heatsinks. The maximum junction temperature T_J for this transistor is 175 °C. The thermal resistance $R_{\theta JA}$ between the junction and surroundings is as high as 62.5 °C/W, which is higher than allowable, even for the lower-power systems. Table 3 gives the maximum thermal resistances for each system. Even a modest heatsink should be enough in each case to dissipate the heat. In the worst case, we can add transistors in parallel, but I don't anticipate this happening: even a simple sheet of aluminum 3 mm thick measuring 20 mm by 14 mm (the transistor package size) has a thermal resistance of a fraction of a degree per watt. (The thermal conductivity of aluminum changes with temperature and alloyed metals, but is in the neighbourhood of 200 W/(m°C), which gives a thermal resistance of 0.05 °C/W for this geometry.)

Table 3: Maximum thermal resistances for each transistor

System	Power for Q_2 (W)	Required $R_{\theta JA}$ (°C/W)
Headlights	7.14	22.41
Highbeams	16.64	7.72
Indicators (each)	3.42	44.83
Taillights	3.56	42.99

The Q_1 transistors do not need the same robustness, as they do not conduct much current. Any small transistor with a reliable threshold voltage is usable, with a smaller threshold preferred, to reduce power consumption. I suggest the 2N3904, which is also cheap and readily available. It has a typical base-emitter threshold of 0.65 V.

The choices of MOSFETs versus BJTs are somewhat arbitrary.

4.2.3 Resistors

The value of R_1 is not critical. It only needs to be much smaller than the off-resistance at the collector of Q_1 (which is very large) to be able to pull up the gate of Q_2. I suggest 100 kΩ, to avoid burning too much power.

The value of R_3 determines the current I_L through the LEDs. These are the values from Table 2. The voltage across these resistors, as mentioned, is the base-emitter saturation voltage of Q_1, which is 0.65 V to 0.85 V for small currents.

Assuming a saturation voltage of 0.7 V, we can calculate the resistance

$$R_3 = \frac{0.7\,\mathrm{V}}{I_L} \tag{1}$$

and the power dissipated by the resistor

$$P_{R_3} = \frac{(0.7\,\mathrm{V})^2}{R_3} \tag{2}$$

The desired values are given in the first columns of Table 4. Some of these are smaller than the smallest readily available resistor values, so I suggest putting several small resistors in parallel. The next columns list the number and values of the resistors in parallel. These have been rounded to the nearest standard values that do not exceed the desired currents. The resulting currents and powers in each light system are given in the final column. For the taillights, one of the parallel resistors is switched for dimming. The given values are for the higher-power (undimmed) case.

The currents total 5.66 A (with undimmed taillights), which corresponds to 50.94 W with the 9 V supply.

Table 4: Calculated specifications for R_3 resistors, and next largest standard values

	Desired value		Next largest standard value			Results when undimmed	
	R_3 (Ω)	P_{R_3} (W)	# in parallel	R_3 (Ω)	P_{R_3} (W)	Current (A)	Power (W)
Headlights	0.5	0.98	2	1	1	1.4	12.6
Highbeams	0.23	2.1	4	1	1	2.8	25.2
Left indicator	1.33	0.37	1	1.5	0.5	0.47	4.23
Right indicator	1.33	0.37	1	1.5	0.5	0.47	4.23
Taillights	1.33	0.37	2	2.7	0.25	0.52	4.68
					Total (undimmed)	5.65	50.87

4.2.4 PWM circuit components

The PWM circuit needs a 555 timer, 2 resistors, and 2 capacitors. Components R_1 and C_2 do no affect the frequency, so I suggest values that will not draw too much power: 100 kΩ and 0.01 µF respectively. The frequency of the output has this dependency:

$$f = \frac{1}{1.386 R_2 C_1}. \tag{3}$$

We want roughly $f = 1.5\,\mathrm{Hz}$. If we also take $R_2 = 100\,\mathrm{k\Omega}$, this gives 4.8 µF. The closest standard size is 4.7 µF, which gives $f = 1.54\,\mathrm{Hz}$, which is acceptable.

4.2.5 Switches

We need two momentary switches for the indicators, and one for the taillight. We also need a sustained on-off switch for the highbeams, and another for the master switch for the system.

4.2.6 Connectors, wire, and PCBs

This section will be expanded once the circuits are working on a breadboard. We can probably use perfboards rather than custom PCBs, as the circuits are quite simple. Remember to size perfboard leads and wires for power ratings. All components will need to withstand the forces from the moving bike. This means testing connectors for looseness, as well as selecting multi-stranded wire to avoid failure.

4.3 Summary: parts list

Table 5: Parts list

Component	Number	Part
Power		Batteries TBD
LEDs	8	1 W white LED
	2	10 W white LED
	8	1 W yellow LED
	8	1 W red LED
Drivers	5	FQP30N06 NMOS transistor
	5	TO-220 package heatsinks with mounting hardware
	1	Thermal paste or film
	5	2N3904 NPN transistor
	5	100 kΩ 0.25 W resistor
	6	1 Ω 1 W resistor
	2	1.5 Ω 0.5 W resistor
	2	2.7 Ω 0.25 W resistor
PWM module	1	555 timer
	2	100 kΩ 0.25 W resistor
	1	0.01 µF capacitor
	1	4.8 µF capacitor
Switches	3	Momentary normally open switch
	2	Sustained on-off switch
Connectors and wire	TBD	
Other		Perfboards (number and size TBD)

4.4 Summary: power consumption

	LEDs	R_3	Q_2	Total	%
Headlights	9.52	0.98	2.1	12.6	25
Highbeams	19.5	1.96	3.74	25.2	50
Left indicator	2.31	0.33	1.56	4.2	8
Right indicator	2.31	0.33	1.56	4.2	8
Taillights	3.99	0.36	0.31	4.67	9
Total	37.63	3.96	9.28	50.87	
%	74	8	18		

Table 6: A breakdown of power consumption in watts (power in PWM and bias circuits is negligible)