

This document was written by Jay Kavanaugh who claims to be a turbosystems engineer at Garrett.

Howdy,

This thread was brought to my attention by a friend of mine in hopes of shedding some light on the issue of exhaust size selection for turbocharged vehicles. Most of the facts have been covered already. FWIW I'm an turbocharger development engineer for Garrett Engine Boosting Systems.

*N/A cars: As most of you know, the design of turbo exhaust systems runs counter to exhaust design for n/a vehicles. N/A cars utilize exhaust **velocity** (not backpressure) in the collector to aid in scavenging other cylinders during the blowdown process. It just so happens that to get the appropriate velocity, you have to squeeze down the diameter of the discharge of the collector (aka the exhaust), which also induces backpressure. The backpressure is an undesirable byproduct of the desire to have a certain degree of exhaust velocity. Go too big, and you lose velocity and its associated beneficial scavenging effect. Too small and the backpressure skyrockets, more than offsetting any gain made by scavenging. There is a happy medium here.*

For turbo cars, you throw all that out the window. You want the exhaust velocity to be high upstream of the turbine (i.e. in the header). You'll notice that primaries of turbo headers are smaller diameter than those of an n/a car of two-thirds the horsepower. The idea is to get the exhaust velocity up quickly, to get the turbo spooling as early as possible. Here, getting the boost up early is a much more effective way to torque than playing with tuned primary lengths and scavenging. The scavenging effects are small compared to what you'd get if you just got boost sooner instead. You have a turbo; you want boost. Just don't go so small on the header's primary diameter that you choke off the high end.

*Downstream of the turbine (aka the turboback exhaust), you want the least backpressure possible. No ifs, ands, or buts. Stick a Hoover on the tailpipe if you can. The general rule of "larger is better" (to the point of diminishing returns) of turboback exhausts is valid. Here, the idea is to minimize the pressure downstream of the turbine in order to make the most effective use of the pressure that is being generated upstream of the turbine. Remember, a turbine operates via a pressure ratio. For a given turbine inlet pressure, you will get the highest pressure **ratio** across the turbine when you have the lowest possible discharge pressure. This means the turbine is able to do the most amount of work possible (i.e. drive the compressor and make boost) with the available inlet pressure.*

Again, less pressure downstream of the turbine is goodness. This approach minimizes the time-to-boost (maximizes boost response) and will improve engine VE throughout the rev range.

As for 2.5" vs. 3.0", the "best" turboback exhaust depends on the amount of flow, or horsepower. At 250 hp, 2.5" is fine. Going to 3" at this power level won't get you much, if

anything, other than a louder exhaust note. 300 hp and you're definitely suboptimal with 2.5". For 400-450 hp, even 3" is on the small side.

As for the geometry of the exhaust at the turbine discharge, the most optimal configuration would be a gradual increase in diameter from the turbine's exducer to the desired exhaust diameter-- via a straight conical diffuser of 7-12° included angle (to minimize flow separation and skin friction losses) mounted right at the turbine discharge. Many turbochargers found in diesels have this diffuser section cast right into the turbine housing. A hyperbolic increase in diameter (like a trumpet snorkus) is theoretically ideal but I've never seen one in use (and doubt it would be measurably superior to a straight diffuser). The wastegate flow would be via a completely divorced (separated from the main turbine discharge flow) dumptube. Due the realities of packaging, cost, and emissions compliance this config is rarely possible on street cars. You will, however, see this type of layout on dedicated race vehicles.

A large "bellmouth" config which combines the turbine discharge and wastegate flow (without a divider between the two) is certainly better than the compromised stock routing, but not as effective as the above.

If an integrated exhaust (non-divorced wastegate flow) is required, keep the wastegate flow separate from the main turbine discharge flow for ~12-18" before reintroducing it. This will minimize the impact on turbine efficiency-- the introduction of the wastegate flow disrupts the flow field of the main turbine discharge flow.

Necking the exhaust down to a suboptimal diameter is never a good idea, but if it is necessary, doing it further downstream is better than doing it close to the turbine discharge since it will minimize the exhaust's contribution to backpressure. Better yet: don't neck down the exhaust at all.

Also, the temperature of the exhaust coming out of a cat is higher than the inlet temperature, due to the exothermic oxidation of unburned hydrocarbons in the cat. So the total heat loss (and density increase) of the gases as it travels down the exhaust is not as prominent as it seems.

Another thing to keep in mind is that cylinder scavenging takes place where the flows from separate cylinders merge (i.e. in the collector). There is no such thing as cylinder scavenging downstream of the turbine, and hence, no reason to desire high exhaust velocity here. You will only introduce unwanted backpressure.

Other things you can do (in addition to choosing an appropriate diameter) to minimize exhaust backpressure in a turboback exhaust are: avoid crush-bent tubes (use mandrel bends); avoid tight-radius turns (keep it as straight as possible); avoid step changes in diameter; avoid "cheated" radii (cuts that are non-perpendicular); use a high flow cat; use a straight-thru perforated core muffler... etc.

Comparing the two bellmouth designs, I've never seen either one so I can only speculate. But based on your description, and assuming neither of them have a divider wall/tongue between the turbine discharge and wg dump, I'd venture that you'd be hard pressed to measure a difference between the two. The more gradual taper intuitively appears more desirable, but it's likely that it's beyond the point of diminishing returns. Either one sounds like it will improve the wastegate's discharge coefficient over the stock config, which will constitute the single biggest difference. This will allow more control over boost creep. Neither is as optimal as the divorced wastegate flow arrangement, however.

There's more to it, though-- if a larger bellmouth is excessively large right at the turbine discharge (a large step diameter increase), there will be an unrecoverable dump loss that will contribute to backpressure. This is why a gradual increase in diameter, like the conical diffuser mentioned earlier, is desirable at the turbine discharge.

As for primary lengths on turbo headers, it is advantageous to use equal-length primaries to time the arrival of the pulses at the turbine equally and to keep cylinder reversion balanced across all cylinders. This will improve boost response and the engine's VE. Equal-length is often difficult to achieve due to tight packaging, fabrication difficulty, and the desire to have runners of the shortest possible length.

Here's a worked example (simplified) of how larger exhausts help turbo cars:

Say you have a turbo operating at a turbine pressure ratio (aka expansion ratio) of 1.8:1. You have a small turboback exhaust that contributes, say, 10 psig backpressure at the turbine discharge at redline. The total backpressure seen by the engine (upstream of the turbine) in this case is:

$$(14.5 + 10) * 1.8 = 44.1 \text{ psia} = 29.6 \text{ psig total backpressure}$$

So here, the turbine contributed 19.6 psig of backpressure to the total.

Now you slap on a proper low-backpressure, big turboback exhaust. Same turbo, same boost, etc. You measure 3 psig backpressure at the turbine discharge. In this case the engine sees just 17 psig total backpressure! And the turbine's contribution to the total backpressure is reduced to 14 psig (note: this is 5.6 psig lower than its contribution in the "small turboback" case).

So in the end, the engine saw a reduction in backpressure of 12.6 psig when you swapped turbobacks in this example. This reduction in backpressure is where all the engine's VE gains come from.

This is why larger exhausts make such big gains on nearly all stock turbo cars-- the turbine compounds the downstream backpressure via its expansion ratio. This is also why bigger turbos make more power at a given boost level-- they improve engine VE by operating at lower turbine expansion ratios for a given boost level.

As you can see, the backpressure penalty of running a too-small exhaust (like 2.5" for 350 hp) will vary depending on the match. At a given power level, a smaller turbo will generally be operating at a higher turbine pressure ratio and so will actually make the engine more sensitive to the backpressure downstream of the turbine than a larger turbine/turbo would. As for output temperatures, I'm not sure I understand the question. Are you referring to compressor outlet temperatures?

The advantage to the bellmouth setup from the wg's perspective is that it allows a less torturous path for the bypassed gases to escape. This makes it more effective in bypassing gases for a given pressure differential and wg valve position. Think of it as improving the VE of the wastegate. If you have a very compromised wg discharge routing, under some conditions the wg may not be able to bypass enough flow to control boost, even when wide open. So the gases go through the turbine instead of the wg, and boost creeps up.

The downside to a bellmouth is that the wg flow still dumps right into the turbine discharge. A divider wall would be beneficial here. And, as mentioned earlier, if you go too big on the bellmouth and the turbine discharge flow sees a rapid area change (regardless of whether the wg flow is being introduced there or not), you will incur a backpressure penalty right at the site of the step. This is why you want gradual area changes in your exhaust.