DSI International

Prognostics in *eXpress*

Informed Recommendations / Informed Diagnostics

Prognostics-Informed Diagnostic Engineering will come naturally to users of ***eXpress***—simply add prognostic definitions and specify the extent to which prognostics are to be taken into account by the diagnostics. The same full-system approach that ***eXpress*** brings to diagnostic engineering will be used to assess the effectiveness of the proposed Prognostic Health Management (PHM) capability. It's really that simple.

Prognostic Candidates – To help identify the failure modes for which it would be most desirable to develop prognostics, ***eXpress*** ranks prognostic candidates based on user-specified criteria.

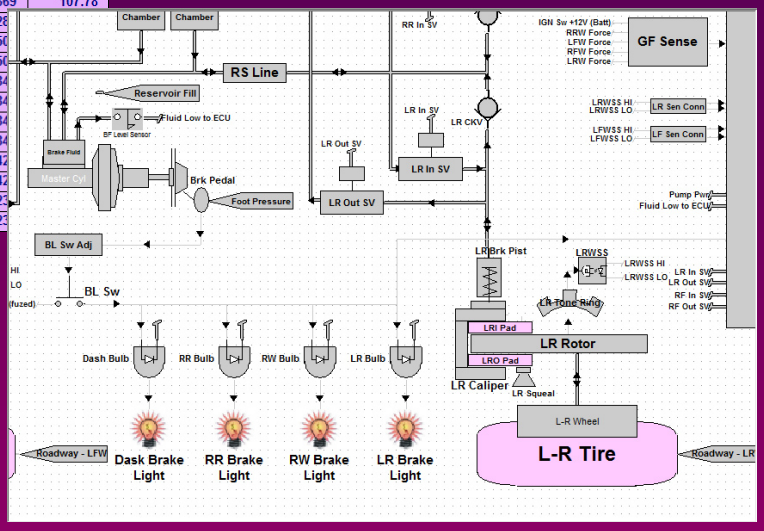
Selected prognostic measurements are represented in ***eXpress*** in terms of their projected behavior—the time before failure (or horizon) that the prognosis is expected and the estimated confidence that the prognosis will occur at or before that horizon.

Prognostic Candidates

##	Failure Mode	Item	Maximum Severity	Failure Probability	Ranking
1	Pad squeeling	Front Pads	Loss of Equipment	0.020211	157.09
2	Pad Squeeling	Front Pads	Loss of Equipment	0.020211	157.09
3	Pad Squeeling	Front Pads	Loss of Equipment	0.020211	157.09
4	Pad Squeeling	Front Pads	Loss of Equipment	0.020211	157.09
5	Pad Squeeling	Rear Pads	Loss of Equipment	0.020211	157.09
6	Pad Squeeling	Rear Pads	Loss of Equipment	0.020211	157.09
7	Pad Squeeling	Rear Pads	Loss of Equipment	0.020211	157.09
8	Pad Squeeling	Rear Pads	Loss of Equipment	0.020211	157.09
9	Switch Fails Open	R Pump	Loss of Life	0.009600	144.83
10	Pedal Linkage Failure	Brk Pedal	Loss of Life	0.005775	123.50
11	LR Brake Light Bulb Failure	LR Bulb	Loss of Equipment	0.013749	121.05
12	RR Brake Light Bulb Failure	RR Bulb	Loss of Equipment	0.013749	121.05
13	RW Brake Light Bulb Failure	RW Bulb	Loss of Equipment	0.013749	121.05
14	Flat tire (puncture)	RF Tire	Loss of Equipment	0.011369	107.78
15	Flat tire (puncture)	RR Tire	Loss of Equipment	0.011369	107.78
16	Flat tire (puncture)	LF Tire	Loss of Equipment	0.011369	107.78
17	Flat tire (puncture)	LR Tire	Loss of Equipment	0.011369	107.78
18	Switch Fails Open	F Pump	Loss of Life	0.00128	
19	Pump Relay Coil Open	Pump Relay	Loss of Life	0.00050	
20	Pump Relay Coil Shorted	Pump Relay	Loss of Life	0.00050	
21	Flat tire (progressive wear)	RF Tire	Loss of Equipment	0.00884	
22	Flat tire (progressive wear)	RR Tire	Loss of Equipment	0.00884	
23	Flat tire (progressive wear)	LF Tire	Loss of Equipment	0.00884	
24	Flat tire (progressive wear)	LR Tire	Loss of Equipment	0.00884	
25	Pump Relay Contact Stuck Closed	Pump Relay	Loss of Life	0.00042	
26	Pump Relay Cotact Stuck Open	Pump Relay	Loss of Life	0.00042	
27	Pump Motor Shorted	F Pump	Loss of Life	0.00023	
28	Pump Motor Shorted	R Pump	Loss of Life	0.00023	

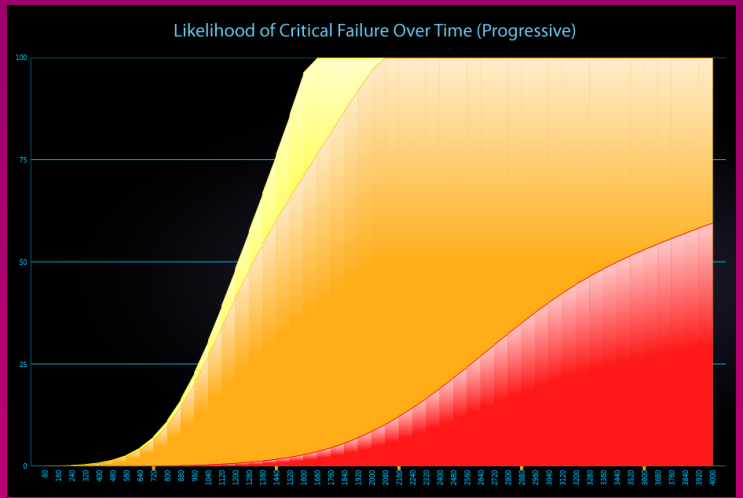
*In this list of Prognostic Candidates generated by **eXpress**, individual failure modes have been ranked based on a user-specified combination of the end effect severity of each failure and its relative likelihood of occurrence.*

Prognostic and Diagnostic Analysis – Collectively, the individual prognostic definitions are used by ***eXpress*** to estimate prognostic performance for an entire system. Moreover, system diagnostics are assessed and optimized to provide a better understanding of diagnostic behavior for systems that are to be supported using prognostics.

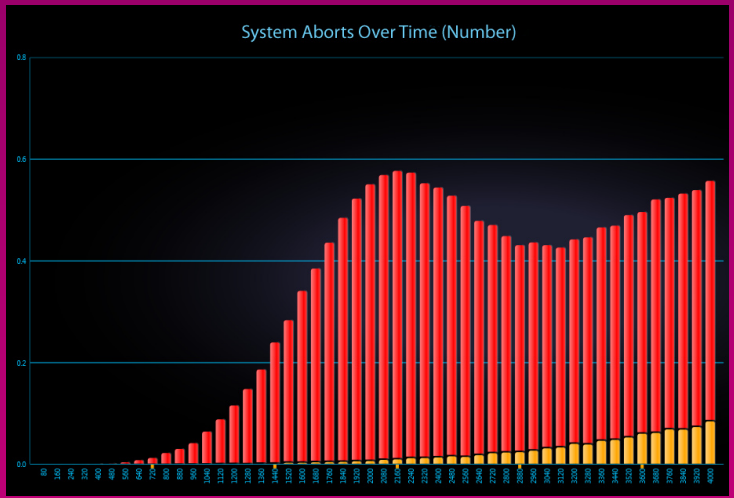


*In this **eXpress** model of an automotive braking system (part of which is pictured above), the brake pads and the tires have been targeted for prognostics.*

Setting the Stage for STAGE – The same prognostic and diagnostic data that is used to perform PHM analyses within ***eXpress*** can be easily exported to STAGE for more extensive, simulation-based analyses and automated trade studies.



The use of prognostics or condition-based maintenance can really reduce the likelihood of critical failure, as can be seen in this chart produced by STAGE.



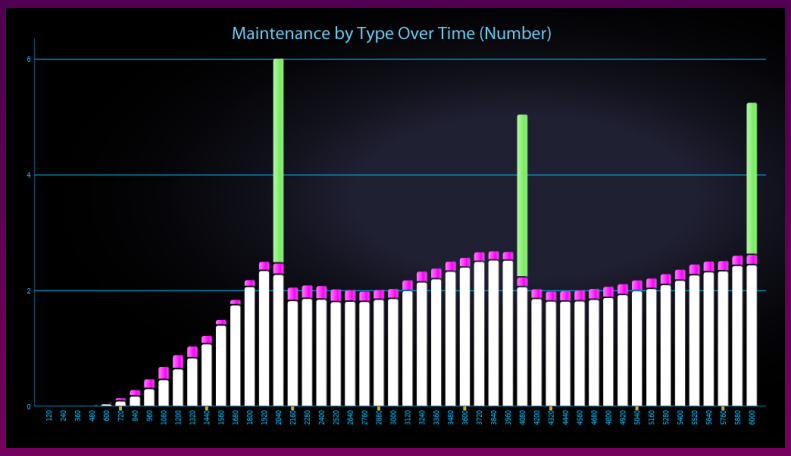
STAGE recognizes when inadequate PHM can result in false system or mission aborts (depicted in red in the above chart, with the "true" aborts shown in orange).

PHM Trade Studies in STAGE

PHM Optimization based on Both Requirements and Constraints – Using STAGE, your overall Prognostic Health Management solution can be evaluated based not only on how well it meets system requirements (some of which are listed below), but also on how well it can be implemented within given cost constraints—including development and other non-recurring engineering (NRE) costs, as well as the continuing costs of ownership. So, if you want to see whether the long-term benefits of those additional prognostic sensors will justify their expensive price tag, try them out on STAGE.

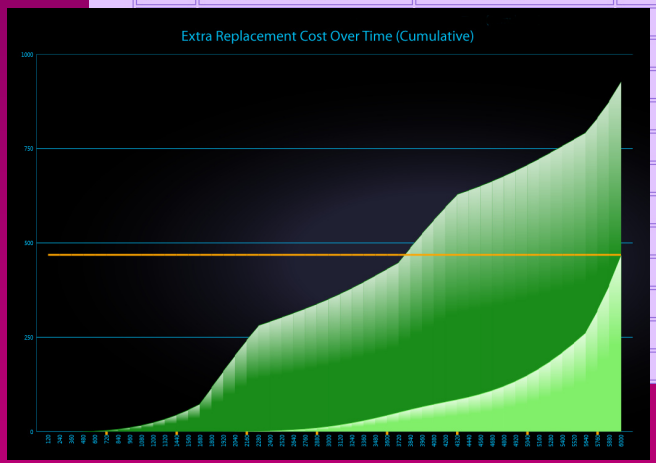
Prognostic Effectiveness	**Critical Failures**	**Mean Time Between Failure**	**Development Costs**
Fault Detection & Isolation	**System Aborts**	**Mean Time to Repair**	**Sustainment Costs**
Diagnostic False Alarms	**Mission Success**	**System Availability**	**Cost of Ownership**

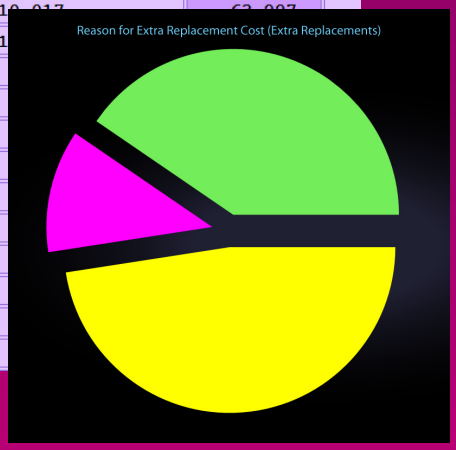
Extensive Cost Analysis – STAGE takes cost very, very seriously, allowing the costs associated with proposed PHM solutions to be examined from a variety of angles. Trade studies in STAGE can list overall maintenance costs, the cost that is "wasted" when items are replaced prior to failure, the cost of "extra" replacements, the labor cost resulting from manual troubleshooting, and NRE costs (including prognostic sensor development). Cost can be categorized by repair item, by test or prognostic measurement, by maintenance type, by the reason for replacement, or even by the size of the associated fault group isolated by the diagnostics.



Reason for Replacement Cost Per Item (Number)

##	Items	Replacement Cost (Item Failure/Wear out)	Replacement Cost (Diagnostic Ambiguity)	Replacement Cost (Prognostics)	Replacement Cost (Scheduled Maintenance)	Totals
1	Master Cyl	52.244	204.057	.000	.000	256.301
2	Brk Pedal	27.322	36.938	.000	.000	64.260
3	FR Line	21.295	26.689	.000	.000	47.984
4	RR Line	21.211	26.618	.000	.000	47.829
5	BL Sw	.334	23.764	.000	.000	24.098
6	BL Sw Adj	.503	23.595	.000	.000	24.098
7	Brake Fluid	18.647	17.340	.000	.000	35.988
			15.731	.000	10.017	
			15.716	.000	1	
			11.834	.000		
			11.664	.000		
			2.314	.000		
			.341	.000		
			.312	.000		
			.028	.000		
			.016	.000		
			.010	.000		
			.003	.000		
			.000	.000		





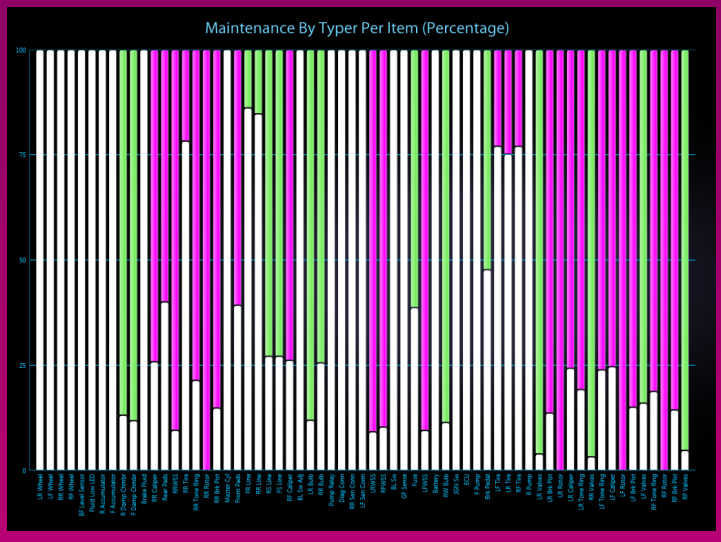
This page presents a small sampling of the many cost-related calculations available in STAGE. In the bar chart at the top, replacement cost over time is categorized by maintenance type (note the periodic spikes as scheduled maintenance is performed). The report in the middle lists the cumulative replacement cost for each item, categorized by the reason that the cost was incurred (in this example, the items have been sorted to show those for which the greatest cost was due to diagnostic ambiguity). The pie chart depicts the costs (categorized by reason) that result from "extra" item replacements—costs that are only incurred because items were previously replaced prior to failure. In this example, "extra" costs result more from earlier false removals (yellow) than either prognostics (magenta) or scheduled maintenance (green). The graph on the left compares the cost of "extra" item replacements (light green) during the simulated time span with the "wasted" portion of the cumulative item replacement costs (darker green), based on the remaining useful life of each replaced item.

Automated Trade Study Analysis – In STAGE, trade studies can be performed by simply saving the results of multiple simulation runs (each representing a different case under consideration). The Simulation Summary Report will automatically list the appropriate metrics side-by-side for easy comparison. Because these metrics are based on the specific calculations that you have selected for each run of the simulation, the resulting summary will include precisely those aspects of the overall health management design that are valuable within that trade study.

Simulation Summary Report

Simulation:	Run to Failure	Sched. Maint. (tight)	Sched. Maint. (loose)	Prognostics
Failure Statistics				
Likelihood of Loss of Operation	100% at 1,280 hours	100% at 1,360 hours	100% at 1,680 hours	100% at 1,520 hours
Likelihood of Loss of Equipment	100% at 1,440 hours	100% at 1,760 hours	100% at 2,000 hours	100% at 1,920 hours
Likelihood of Loss of Life	62.098% at 4,000 hours	61.537% at 4,000 hours	62.612% at 4,000 hours	61.904% at 4,000 hours
Prognostic Statistics				
Critical Failures Prognosed	N/A	N/A	N/A	4.787 (27.007%)
Critical Failures Not Prognosed: Loss of Operation	2.780 (15.694%)	2.828 (20.004%)	2.800 (26.677%)	2.787 (15.721%)
Critical Failures Not Prognosed: Loss of Equipment	14.255 (80.486%)	10.622 (75.143%)	7.015 (66.830%)	9.480 (53.484%)
Critical Failures Not Prognosed: Loss of Life	0.677 (3.820%)	0.686 (4.853%)	0.682 (6.493%)	0.672 (3.788%)
Maintenance Statistics				
Corrective Maintenance	54.646 (100.000%)	51.753 (87.637%)	46.943 (72.724%)	50.747 (90.984%)
Scheduled Maintenance	N/A	7.301 (12.363%)	17.607 (27.276%)	N/A
Maintenance due to Prognostics	N/A	N/A	N/A	5.029 (9.016%)
Replacement Statistics				
Replacements due to Item Failure	42.157 (77.146%)	39.143 (66.283%)	34.320 (53.168%)	38.130 (68.362%)
Replacements due to Diagnostic Ambiguity	12.489 (22.854%)	12.611 (21.354%)	12.623 (19.556%)	12.618 (22.622%)
Replacements due to Prognostics	N/A	N/A	N/A	5.029 (9.016%)
Replacements due to Scheduled Maintenance	N/A	7.301 (12.363%)	17.607 (27.276%)	N/A
Remaining Useful Life Per Replacement	1,392.812 hours (3.164%)	1,507.617 hours (5.347%)	1,634.176 hours (9.279%)	1,480.756 hours (6.409%)
Remaining Useful Life Per Early Replacement	2,222.812 hours (4.791%)	2,322.021 hours (7.652%)	2,418.948 hours (12.072%)	2,287.480 hours (9.290%)
Cost-Related Statistics				
Wasted Item Cost	274.53	680.85	1,162.97	392.29
Wasted Item Cost due to False Removals	274.53 (100.000%)	279.49 (41.050%)	276.79 (23.800%)	279.03 (71.130%)
Wasted Item Cost due to Prognostics	N/A	N/A	N/A	113.25 (28.870%)
Wasted Item Cost due to Scheduled Maintenance	N/A	401.36 (58.950%)	886.18 (76.200%)	N/A
Cost of Extra Replacements	105.24	399.31	694.67	133.24
Cost of Extra Replacements due to False Removals	105.24 (100.000%)	109.74 (27.483%)	105.26 (15.152%)	110.55 (82.965%)
Cost of Extra Replacements due to Prognostics	N/A	N/A	N/A	22.70 (17.035%)
Cost of Extra Replacements due to Scheduled Maintenance	N/A	289.57 (72.517%)	589.41 (84.848%)	N/A

This Simulation Summary Report from STAGE lists the results from four separate simulation runs—each of which employs a different approach to maintaining the system. Although this specific example might be used to compare the relative merits of the different approaches, STAGE also allows you to simulate and compare the impact of more "balanced" maintenance plans (where each case utilizes multiple approaches to maintain the system).



The above graph shows the different approaches used to maintain each item in this sample system. The percentage of each item's replacements that result from corrective maintenance are colored white, replacements based on prognostics are magenta, and replacements due to scheduled maintenance are light green. In STAGE, trade studies can be easily developed to compare the impact of different PHM "cocktails".

Achieving a Balance – Over the years, there have been numerous attempts at monological health maintenance—systems for which all critical failures were to be averted using extensive redundancy or eliminated altogether by prognostics. For the majority of complex systems, however, the most feasible solution is often a balanced PHM "cocktail" that employs multiple means to prevent critical failures.

STAGE provides a flexible and extensible platform upon which to evaluate the trade-offs between the development of expensive (and unproven) prognostic sensors, the use of wasteful or ineffective maintenance schedules, and the addition of space or weight-consuming hardware redundancy. The reviews are in—when you develop your next PHM solution, STAGE analysis should be seated front and center.

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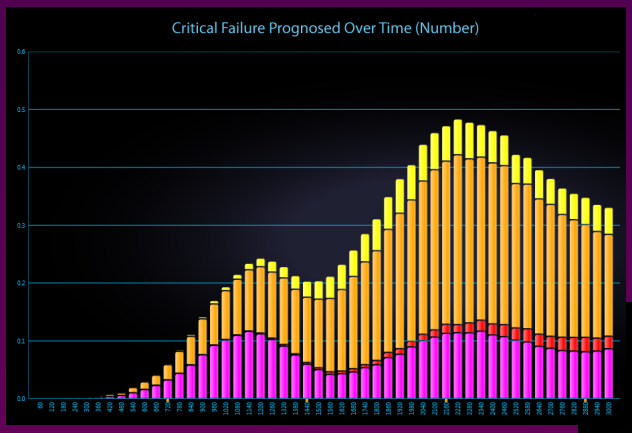
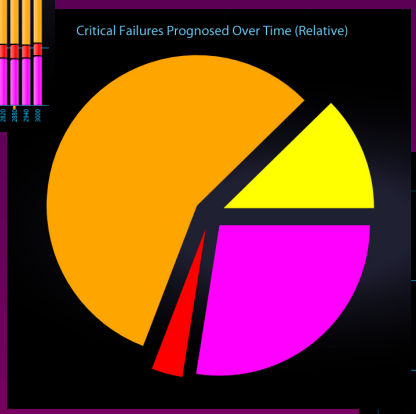
Prognostic Analysis in STAGE

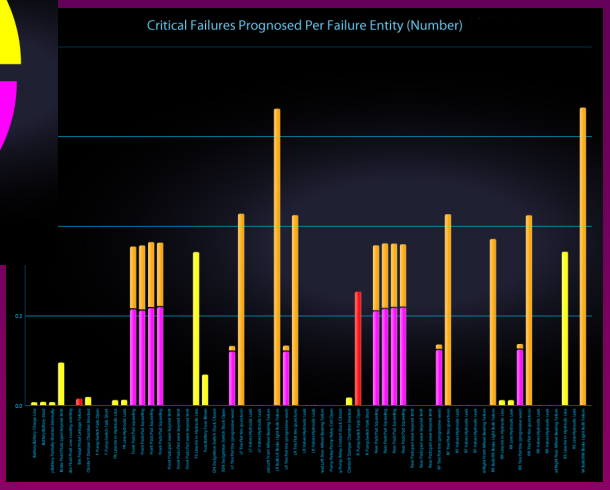
PHM from a Variety of Perspectives

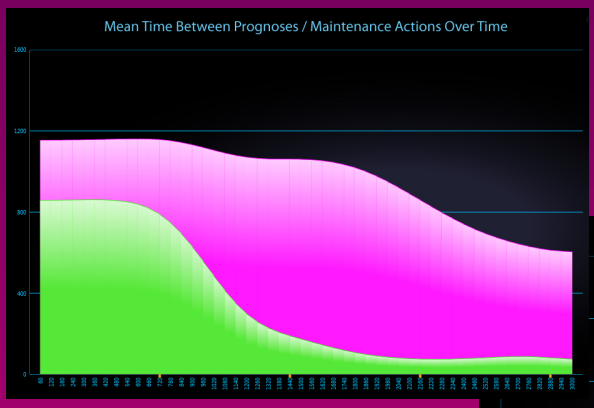


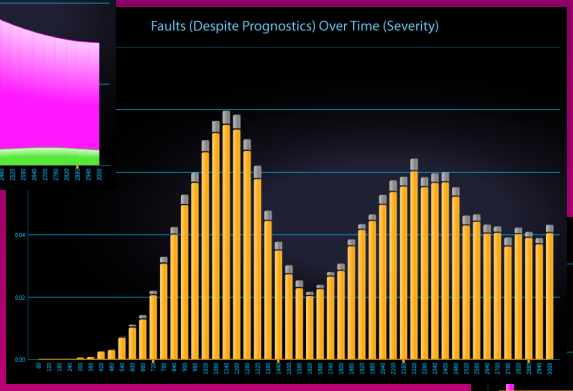
In-Depth Analyses of Prognostic Effectiveness – Once the diagnostic model and prognostic definitions have been imported from ***eXpress***, STAGE can then be used to analyze the effectiveness of the proposed prognostic solution. Included in STAGE's stock calculations are a number of prognostics-related graphs and reports (a few of which are depicted on this page), allowing prognostic performance to be evaluated from a variety of perspectives.



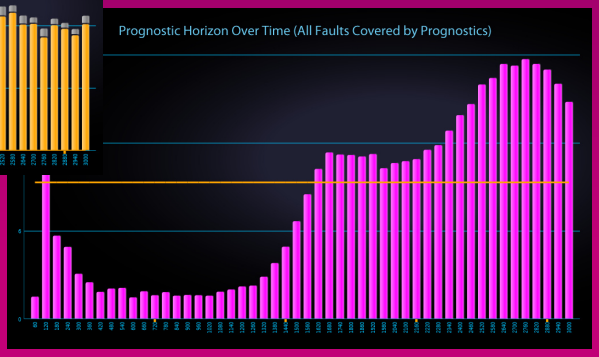
Charts and Reports – Every calculation in STAGE can be viewed either as a chart or as a report. You may wish to use the charts to track trends over time and the reports to investigate the causes behind those trends.







Presentation-Ready – Any of the charts produced by STAGE can be easily exported to a graphic file that can be directly incorporated into your own reports and presentations. There's nothing quite like a graph to explain complex prognostic behavior over time.



Above, the top three STAGE analysis charts all depict how critical failures are handled in a given system. Prognosed critical failures are colored magenta, whereas unprognosed critical failures are color-coded by severity (the most severe failures, for instance, are colored red). The first chart shows critical failures over time, the pie chart depicts the overall percentages, and the chart on the right breaks down critical failures by failure mode. The bottom three charts depict the Mean Time Between Prognoses, Faults that Occur Despite Prognostics and the Average Prognostic Horizon Over Time.

For additional information about ***eXpress*** and STAGE, contact DSI or one of its international representatives:

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