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ENGINEERING **RESEARCH REPORT · Engineering research report**

Reliability of Vacuum Gripping and Dynamic Rotation of Curved Automotive Glass

Public-source research, engineering derivation, and verification methods for assisted handling and custom tooling in the automotive industry

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Research and Verification Methods · Not Product Certification or Evidence of Customer Acceptance

Report structure

> Research Boundary Standards, papers, and vendor data in the main text are used to support the methodological framework; example calculations contain assumptions. Project applications must be supplemented with real workpiece, tooling, action curves, risk assessments and original test evidence.

> Research boundary — Document type: public-source research and engineering verification methods. This report does not claim that any specific tool, glass model, or production line has passed testing. Example parameters and criteria shall be reconfirmed using actual parts and the project risk assessment.

00 Executive Summary

Windshields, rear windows, side windows, and panoramic canopies have airtight surfaces that are generally suitable for vacuum handling, but their curvature, laminate construction, silkscreen/coating, edge fragility, and dynamic flipping make reliability issues significantly different from flat glass. Whether suction cup can form a stable seal depends not only on the pressure difference and area, but also on the contact geometry, preload, bending and sealing lip load distribution between suction cup and the local curved surface. IEEE's suction cup modeling study separated axial compression and bending force, and verified the load-bearing prediction idea through curved surface tests [1]; industrial data emphasizes the role of flexible sealing lips, corrugation compensation, limited support surfaces and low-imprint materials in automotive glass [2][3].

During dynamic rotation, load is continuously redistributed among normal force, tangential force, and moment. Tooling that maintains stable vacuum in the initial vertical orientation may experience its maximum rotation torque at the intermediate 45° orientation because of combined center-of-gravity offset, or may fail in the horizontal orientation because glass deflection redistributes suction-point loads. Engineering design shall therefore treat seal establishment, holding, full-angle rotation, positioning, support-confirmed release, and abnormal controlled set-down as one continuous state machine.

Core conclusion

- The number and total area of the suction cups are only the starting point. Matching the local curvature, correctly preloading the sealing lip, and aligning each suction-cup center axis with the local surface normal are prerequisites for reliable suction.
- Dynamic flipping should calculate the gravity component, eccentric moment, inertia moment and braking demand according to the attitude angle. During verification, vacuum, angle, acceleration and relative slip should be continuously collected.
- The vacuum system shall use appropriate zoning, check valves/energy storage, inhibition of motion at low vacuum, and support-confirmed release. Pressure-retention time shall be derived from leakage curves rather than an empirical constant.
- Glass protection needs to simultaneously control edge impacts, metal proximity, suction cup marks, chemical fingerprints and cleaning particles.
- Reliability release should cover the combination of curvature limit, surface condition, temperature, protective film, accessories, incoming material deviation and suction cup wear.

01 Research objects and applicable boundaries

The research object is automotive safety glass and its pre-assembly assembly, including laminated windshields, tempered side windows/rear windows, glass with silk screen, coating, heating wire, wrapping, positioning pins, wiring harness or camera bracket. GB 9656-2021 provides safety technical specifications for motor vehicle glass [4], and ISO 3537:2015 specifies mechanical test methods for safety glass materials [5]. These product standards do not directly give handling tooling parameters, but remind designers: glass is a product defined by safety performance, and tooling should not introduce unassessed scratches, chipping, local damage or coating effects.

This report covers vacuum tooling on manually guided Pneumatic Industrial Manipulators, robot end effectors, and purpose-built rotation mechanisms. It excludes forming in glass-manufacturing furnaces, complete-vehicle crash performance, and adhesive-curing processes. Customer requirements for appearance, optics, or coatings shall be governed by the customer's latest technical specifications.

Data category	Required input	Impact on tooling design
glass geometry	Three-dimensional surface, thickness, dimensions, local curvature, edge profile	suction cup type, local normal, layout and envelope
Quality attributes	Glass mass, accessory mass, combined center of gravity, inertia	Lifting capacity, tilting axis and braking torque
surface system	Silk screen printing, coating, protective film, ink, cleaner	Permitted suction zones, material compatibility, and marking
Assembly accessories	Edge encapsulation, pins, wiring harnesses, brackets, adhesive-bead paths	Restricted area, tooling avoidance and release path
Incoming material status	Rack angle, pane spacing, adhered panes, placement variation	Approach sequence, suction confirmation, and pane-separation motion

02 Curved surface sealing and suction load-bearing model

02.1 Conditions for seal formation

The first question in suction on a curved surface is not how much weight it can carry, but whether the sealing lip can maintain continuous contact under limited preload. Excessive misalignment between the suction-cup center axis and the local surface normal over-compresses one side of the sealing lip and lifts the other. Bellows and flexible connections can accommodate angular and height differences, but they also increase orientation compliance and tangential displacement. Suction-cup model studies show that contact geometry, axial compression, and bending deformation jointly determine sealing and load capacity [1].

In engineering, the following constraints can be used to filter suction points:

- Within the effective sealing diameter range of suction cup, the glass curvature is compatible with the allowable curvature of suction cup.
- The suction-cup preload displacement shall remain within the supplier-recommended range; do not force the manipulator against the glass to compensate for incorrect alignment.
- The sealing lip completely avoids silk screen steps, protective film folds, holes and accessory boundaries.
- The flexible support stroke can absorb the incoming material deviation, but will not lose sufficient anti-swing stability once it is in place.

02.2 Normal, tangential and combined loads

$$F_{N,usable} = (\Delta p_{min} \cdot \Sigma A_{eff} \cdot \eta_{curve} \cdot \eta_{surface}) / S_N$$

Here, η_{curve} is the reduction factor for curvature and orientation, and $\eta_{surface}$ is the reduction factor for surface condition, contamination, temperature, and wear. Gravity on vertical glass creates primarily a tangential demand; during rotation, the normal and tangential components vary with angle. If θ is defined as the angle between the glass normal and the vertical direction, resolve gravity and inertia in the project coordinate system and calculate suction-cup load distribution at every discrete orientation, rather than checking only the 0° and 90° endpoints.

$$F_{T,demand}(\theta) = m \cdot |g_T(\theta) + a_T(\theta)| + F_{route}(\theta)$$
$$M_{demand}(\theta) = mge \cdot \sin(\theta) + I\alpha + c\omega + M_{disturbance}$$

In the formula, e is the eccentricity from the center of gravity of the glass-tooling combination to the flip axis, I is the moment of inertia, α and ω are the angular acceleration and angular velocity, and $c\omega$ represents the equivalent damping term. The maximum torque does not necessarily occur at the end point and must be checked with the complete action curve.

03 suction cup layout and vacuum architecture

The suction cups shall form a stable support polygon around the combined center of gravity while avoiding edges, black ceramic-print steps, heater-connection areas, camera/sensor brackets, edge encapsulation, and adhesive-bead paths. For large glass, control cup spacing so that local deflection and center sag remain within product limits. The layout shall also preserve the operator's view during installation: the tooling shall not obscure critical locating points or enter collision zones around the A-pillars, headliner, or instrument panel as it approaches the body.

03.1 Vacuum partition

The objective of vacuum zoning is to limit propagation of a single-point leak and improve diagnosability, not simply to make every suction cup independent. Each zone shall have sufficient residual capacity, suitable check valves, and a measurable pressure point. Sensor locations shall represent the state at the suction-cup side rather than only the vacuum-source outlet. Excessive zoning adds valves, lines, and leak points, so reliability and maintainability must be balanced.

Hierarchy	Design points	target state at failure
vacuum generation	Can cover establishment time and known leaks, with operational monitoring	Do not permit a new lifting cycle when source capacity is insufficient
Vacuum Zoning and Check Valves	A single zone failure does not immediately bring down all suction cup	Maintain, stop dangerous actions, and alarm
Energy storage/volume	Provides time for controlled placement and does not replace mechanical safety measures	Pressure decay is predictable and diagnosable
threshold monitoring	Separate establishment thresholds, operational thresholds and alert thresholds	Limit flip/release when threshold is crossed
release loop	Vent only when the glass is supported and the orientation permits release	Refuse to release if any condition is not met

03.2 Pressure holding and leakage curve

The ideal-gas equation cannot fully describe actual leakage as sealing-lip contact changes with load. Measure the Δp(t) curve on actual glass and determine the time window from the operating threshold to the minimum holding threshold under worst-case surface condition, temperature, suction-cup wear, and orientation. If a local interval approximates exponential decay, fit the time constant τ using the following equation, but base acceptance on the envelope of the measured curves.

$$\Delta p(t) \approx \Delta p_0 \cdot \exp(-t/\tau)$$

04 Dynamic flipping and operator control

The flip axis should be as close as possible to the center of gravity of the combination to reduce operator force and braking burden. Complete center-of-gravity balancing is not always optimal: a controlled sense of direction needs to be retained while preventing the glass from flipping over on its own. Rotating mechanisms should have verifiable braking/locking capabilities and controlled release, and hoses and cables must be free from pulling, bending, and snagging at all angles.

04.1 Example torque (only method explained)

Assume the combined mass of the glass and tooling is 40 kg and the combined center of gravity is offset 0.08 m from the rotation axis; the peak gravitational eccentric torque is approximately 31.4 N·m. If maximum inertial torque is estimated at 8 N·m, and friction variation and external disturbances are also considered, the brake, lock, and permitted operator force shall be designed with additional margin based on the risk assessment. The values 40 kg, 0.08 m, and 8 N·m are example assumptions and are not ratings for any product.

The dynamic test should be set up in two layers: slow exploration trajectory and production trajectory. First confirm seals, envelopes and pipelines at low energy, then gradually increase speed and acceleration; only change one main variable at each change, and retain the data version. Trial and error directly at production speed amplifies the risk of glass damage and falls.

05 Glass surface, edge and accessory protection

Schmalz's automotive glass data points out that suction cup marks are related to the structure, material and relative movement of the sealing lip on the glass surface, and contamination particles will amplify the risk of marks [2]. Therefore, "low-marking materials" are not exempt from inspection. Sample validation should be completed for each glass, surface, cleaning agent, contact time and temperature combination.

risk	mechanism	control measures	Check method
suction cup imprint	Material migration, slippage, local surface pressure	Specify material, limit slip and contact time	Check under specified lighting/angle
scratch	Grit, metal proximity, dirty gloves	Cleanliness classification, soft separation, and enclosed storage	Surface magnification inspection and defect map
Edge chipping/micro cracks	Edge impact, snagging on a rack edge, tooling interference	Safe edge clearance, guidance, and low-speed removal from the rack	Visual, dedicated inspection or customer regulations
Attachment force	The wiring harness/bracket is caught by tooling	Three-dimensional prohibited/restricted zones and path check	Full attitude envelope verification
Coating/silk screen effect	Chemical incompatibility or unstable step seal	Permitted suction zone and material-compatibility test	Process approval and appearance/function retest

There is also a risk of adhered panes and sudden separation when removing glass from a rack. The tooling must confirm that a single pane has separated from the rack and, where necessary, use a controlled short stroke, inter-pane sensing, or an auxiliary separation method. Do not rely on rapid pull-off to separate adhered panes.

06 Verification Matrix and Fault Injection

Verification scenario	variable combination	Record signal	Main criteria

Verification scenario	variable combination	Record signal	Main criteria
curvature limit	Minimum/maximum curvature, incoming material deviation	Vacuum and preload displacement of each zone	All key areas are stably established
surface boundary	Cleaning, specified contamination, protective film, temperature	Vacuum-establishment time, pressure decay, marking	No threshold exceedance and acceptable surface condition
Full-angle rotation	Continuous trajectory from 0° to target angle	Angle, velocity, acceleration, vacuum, slip	No peeling, slipping or uncontrolled rotation
Emergency stop/brake	The most unfavorable angle and speed	Stopping time, peak acceleration, torque	No falling, no collision, recoverable
single zone leak	Create a controlled leak or isolate one suction cup	Zone pressure, control status	Stop hazardous motion while retaining sufficient time for controlled set-down
Release command by mistake	Glass suspended / not supported	Release valve and status feedback	The command is rejected and an alarm is generated.
Retest after durability	Representative cycles and cleaning cycles	Leakage trends, material wear, marks	Maintenance thresholds can be detected and performance can be maintained

Fault injection shall begin with low energy, surrogate loads, and simulated signals; actual glass shall be used only at the final stage under controlled-risk conditions. Each test shall define the injection location and time, expected system state, permitted response window, recovery conditions, and evidence file. Fault injection is not intended to prove that failure is impossible; it confirms that a single fault or foreseeable combination of faults does not directly cause a hazardous release.

07 FMEA and control state machine

failure mode	Consequences	Detection/Control	Safe recovery
suction cup does not fit completely	Slow leak or peeling after lifting	Partition establishment time and pressure trend	Do not permit departure from the rack; re-establish suction
Single zone pipeline rupture	Vacuum drops rapidly	Check valve, per-zone sensing, and threshold interlock	Stop rotation and perform a controlled set-down

failure mode	Consequences	Detection/Control	Safe recovery
Angle sensing abnormality	Wrong brake/release permission	Rationality check, mechanical limit	Lockout and manual diagnosis
Brake is not locked	Flip and collide on its own	Locking feedback, torque/position abnormality	Limited movement, safe support
Wrong glass model	Suction points enter restricted areas or path interference	Vehicle model–tooling–recipe consistency	Inhibit suction and lifting
Release valve sticking	Accidental air intake	Valve status diagnosis, dual condition release	Geometric support / per-zone pressure retention
suction cup contamination wear	Marks, leaks, scratches	Cleaning inspection, life and trend monitoring	First item confirmed after replacement

The recommended state machine includes: unloaded safe state, approach, preload, vacuum establishment, suction confirmation, departure from the rack, transport, rotation, positioning, support confirmation, release permission, release complete, and abnormal-load retention. Any sensor conflict, communication interruption, or threshold exceedance shall place the system in the conservative state: retain the load, stop hazardous motion, and inhibit release. Recovery shall first clear the fault and confirm that the glass is in a supported position.

08 Implementation information and conclusions

Engineering deliverables shall include at least the glass-family parameter matrix, permitted suction zones, local surface normals and suction-cup installation drawing, vacuum zoning and thresholds, rotation-axis and torque calculations, trajectory envelope, fault-state table, raw data from actual-part tests, surface-inspection rules, maintenance intervals, and abnormal set-down instructions. At multi-model mixed-production stations, interlock the glass model, tooling module, and control recipe for consistency.

Reliable vacuum handling of curved automotive glass depends on four closed loops: a genuine geometric seal, adequate load margin at every orientation, monitored control without inadvertent release, and preservation of surface and edge quality. No single measure can replace complete verification. This report may serve as the basis for design reviews and test plans, but it is not product certification, customer acceptance, or a third-party test report.

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